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Mexican salamanders never undergo metamorphosis from larval stage to adult, which saves energy, helping them to survive in harsh climates.

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FROM THE EDITOR

Amazing Animals

IN AFRICA, A SPECIES OF TERMITE BUILDS COLUMNS OF MUD AND SPIT, SOMETIMES up to 18 feet tall. Paper wasps with brains the size of two grains of sand can recognize the faces of their fellow wasps. On the seafloor, dozens of unique marine bacteria, worms and crustaceans make their homes within rotting bones of dead whales.

Why do animals do such strange things? In this issue, scientists offer answers to this question. They also reveal surprising discoveries about how animals think and feel. And they explain how some of the oddest creatures ever to roam the earth came by their weird traits.

The animal behaviors that seem peculiar to us humans actually make a lot of sense for survival. Take, for instance, those termites. It turns out that their mud house is climate-controlled—the CO_2 from the bugs' respiration rises out of the top of the mound, whereas at night the outer chambers of the column let in oxygen to keep the critters from suffocating (*page 8*). Other insects have crueler survival tactics. The female jewel wasp injects venom directly into a cockroach's brain to paralyze it, preserve it and feed it to her unborn spawn (*page 32*).

Humans tend to think that we are unique in our intelligence, social skill and depth of emotion. Yet we think too much of ourselves. The humble chicken, for example, is strikingly clever. Males secretly subvert the pecking order—going behind the back of their more dominant rivals to court females (*page 46*). In the horse world, mares seem to provide the social glue to the herd—a job once attributed to stallions (*page 52*). Some wild animals even show what could be construed as grief: dolphins will carry the body of their dead calves with them, and elephants will revisit the bones of lost herd members for years after they die (*page 64*).

And then there are animals that are simply jaw dropping. The prehistoric bird *Pelagornis sandersi*, with its 24-foot wingspan—more than twice the wingspan of the albatross—was an unparalleled ocean soarer (*page 74*). And deep in the tunnels of wetlands, a tiny mole with a fleshy, pink nose the shape of a star devours up to five items of prey a second (*page 82*).

Enjoy this tour of the secret lives of animals. My guess is that you will feel somewhat at home, even among the strangest creatures. After all, we are animals, too. SA

Andrea Gawrylewski
Collections Editor
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SPECIAL EDITION

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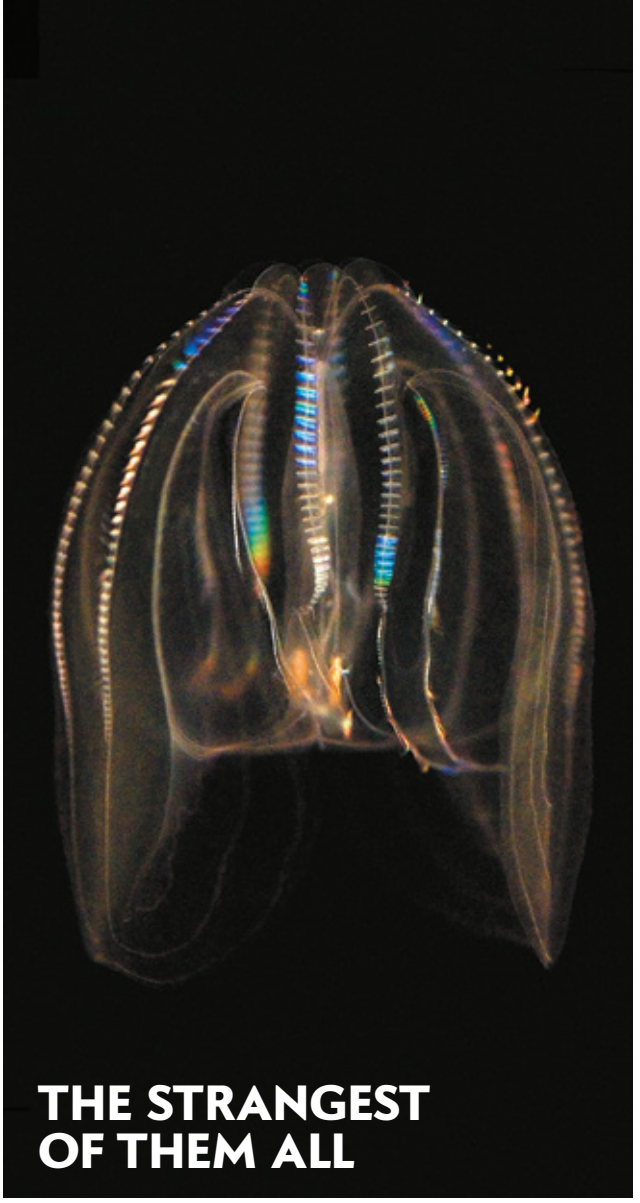

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STRANGER IN THEIR MIDST: Ant-mimicking spider lurks below a group of Asian weaver ants—the species that the spider has evolved to resemble.

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THE SPIDER'S CHARADE

Some arachnids go to extraordinary lengths to mimic the appearance and behavior of ants

By Ximena Nelson

IN BRIEF

Mimicry is a phenomenon in which one species evolves to resemble another. **Species that masquerade** as ants are the most common kind of mimic. Yet they have been the least understood. **But recent studies** have pulled back the curtain on ant impersonators—and in so doing have revealed that mimicry is far more complex than once was thought. **It turns out that** animals exploit mimicry for many reasons—and they pay a price for the advantages it affords.

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IMPOSTERS ABOUND IN THE ANIMAL KINGDOM. PERUSE ANY TEXTBOOK DESCRIPTION of mimicry—in which one species evolves to resemble another—and you will encounter various classic examples, such as the king snake, which copies the coral snake, or the hoverfly, which masquerades as a bee. Less familiar but in many ways even more fascinating are the mimics in a genus of jumping spider known as *Myrmarachne,* which look for all the world like ants. Unlike other jumping spiders, with their furry, round bodies, *Myrmarachne* species have smooth, elongate bodies that give the appearance of having the three distinct parts—head, thorax and abdomen—of ants, despite having just two.

To complete the charade, the spiders walk on their three rear pairs of legs and raise the fourth pair overhead, waving them around to simulate ant antennae. They even adopt ants' characteristically fast, erratic, nonstop mode of locomotion in place of the stop-and-go movements other jumping spiders make. It is an Oscar-worthy performance and the secret of this group's success: more than 200 species of *Myrmarachne* thrive in the tropical forests of Africa, Asia, Australia and the Americas. This rich diversity makes ant mimicry the most common form of mimicry. Yet it is the least known.

New research is exposing the mind-boggling complexity of the ant mimics' charade, however. Like the king snake and hoverfly, *Myrmarachne* species gain a survival advantage by looking like other species—in this case, lethal ant species, because predators of spiders steer clear of both the ants and their lookalikes. But, it turns out, the spiders pay for that advantage: to give a convincing performance, they must expose themselves to considerable risk. The evolutionary forces that led to their fakery have left the ant-mimicking spiders living on the knife's edge, walking a fine line between avoiding one enemy and falling prey to another. In revealing the unexpected perils of mimicry, studies of these remarkable arachnids show the phenomenon of mimicry in a new light.

FAKING IT

MY FASCINATION WITH MIMICRY began one day in 1995 in the office of my then supervisor, Robert R. Jackson, while discussing potential research topics for my master's degree. Jackson, a spider expert at the University of Canterbury in New Zealand, had cemented his reputation as a leading arachnologist through his work on *Portia,* a genus of jumping spiders renowned for their mammalianlike levels of clever behavior. Accordingly, he suggested that I work on a species of *Portia*. As an afterthought, he mentioned the antlike jumping spiders found in the tropics. I was instantly intrigued. We eventually became colleagues, sharing a laboratory, and for 20 years we traveled throughout Africa, Australia and Asia to research these remarkable creatures. Throughout our journeys we have discovered many unusual consequences of mimicry that underscore just how much more complicated the business of deception is than conventional wisdom would suggest.

The standard view originated with English naturalist Henry Walter Bates, who in 1861 provided the first scientific theory to explain mimicry in nature, based on his observations of Amazonian butterflies. Bates supposed that an edible species that resembled an unpalatable or downright toxic one would gain a survival advantage by tricking potential predators into leaving it alone. In Bates's scenario, predators would learn from experience that eating the nasty species was a bad idea. After that unpleasant encounter, the predators would avoid the toxic species and would then avoid the mimics, too—even though the mimics themselves were harmless. This "parasitic" charade, in which one species exploits another's defenses, is now known as Batesian mimicry.

But it turns out that mimicry does not work exclusively in the simple, straightforward manner Bates described—far from it. For one thing, some mimics use their resemblance to another animal not to avoid getting eaten but to deceive their own prey and thus obtain a meal through dishonest signals—so-called aggressive mimicry. And animals exploit mimicry for various other reasons. No group of organisms illustrates the complexities of the strategy, and the evolutionary forces that shaped them, better than do ant-mimicking spiders.

UPSIDES AND DOWNSIDES

TO THE UNINITIATED, ants might seem unworthy of imitation. But in the tropical rain forest, where their total biomass exceeds that of all vertebrate animals combined, ants are strong shapers of the environment and have great power over its inhabitants. As such, they are prime candidates for being imitated.

Myrmarachne spiders trade on the ants' fearsome reputations: ants avidly defend their nests by biting or stinging intruders, and an individual can recruit an entire colony to its cause—often with lethal consequences for the interloper. Predators are

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thus wise to avoid trying to eat any prey that look to be such ants. Yet for the spiders to trick predators into avoiding them, they must take some real risks. For instance, they need to live near the ants to avoid standing out to predators as being not antlike. Living in close quarters, which is unusual for spider species but common in ants, puts the spiders directly in harm's way; if they are found to be fraudsters, odds are they will become lunch.

Having to cohabit with their enemies is not the only price these ant-mimicking spiders pay. The dissemblers are so convincing that predators that specialize in eating ants—including some other species of jumping spiders—attack them as prey. And competition between males for access to females has raised this predation risk. The choosy females have driven *Myrmarachne* males to evolve enlarged mouthparts that can increase their body length by up to 50 percent. Exactly why the females prefer a big mouth is not known, although it may be an indicator of health. At first glance, one would be forgiven for thinking that this enlargement would hurt the spiders' chances of surviving by detracting from their antlike appearance. It does hurt them but not in that way. The trait makes them look like ants that are carrying something in their mouth. Because an ant's mouthparts are very dangerous, ant-eating jumping spiders tend to preferentially target ants that are carrying objects in their jaw and that are thus unable to bite their predators. So although having a big mouth may help male *Myrmarachne* spiders score with the ladies, it also has the unwelcome effect of making them more attractive to predators.

The cunning mimics can actively defend themselves against some of these threats, exhibiting a surprising degree of behavioral flexibility. For example, when an ant-eating jumping spider initiates stalking, the mimic makes a display toward the potential predator, raising its front legs from their normal antennae posture to a position vertically above the head and staring fixedly at the other spider without moving. The display seems to communicate that it is a spider or at least that it is not an ant after all. Whatever the message, it effectively deters the predator. Similarly, when a pesky scientist (and presumably other potential predators) comes along and tries to catch a *Myrmarachne* spider clinging to a plant, the mimic will abandon its antlike behavior, drop off the vegetation and hang out of sight on a thread of silk—the best of both worlds.

One particularly Machiavellian species of ant mimic, *Myrmarachne melanotarsa,* gets the best of both worlds in yet another way and upends the notion that parasitic and aggressive forms are separate phenomena that arise from distinct selective pressures. The spider's resemblance to ants is so terrifying to other, ordinary jumping spiders that in addition to avoiding predation, *M. melanotarsa* uses its antlike appearance to capture prey. It drives hapless jumping spider mothers out of their nests; then it penetrates the nest to raid the eggs or the brood of spiderlings. Ants have trouble raiding spider nests because their legs get caught in the spider silk, but spiders have adaptations that enable them to negotiate the sticky strands—and *M. melanotarsa* takes full advantage of them.

LEARNED OR INSTINCTIVE?

TO FULLY TEASE OUT the forces that have caused mimicry to evolve and take the forms it does, researchers need to know the factors that cause predators to avoid imposters. Back in the 1800s, Bates thought that the predator must experience, in some way, the danger posed by a creature that another organism is mimicking before it grasps that it ought to steer clear of the real McCoy and anything that looks like it. But here again the ant-mimicking spiders flout that conventional wisdom. The ordinary jumping spiders that abstain from eating both ants and *Myrmarachne* do so from instinct, not as a result of learning through bad experiences. In other words, the forces that shape evolution have baked that avoidance into the predators' hard wiring.

In hindsight, this avoidance instinct is not surprising: after all, if you die in an encounter with an ant, there is no room for learning. In some ways, it is easier to envision how hardwired avoidance could have evolved: predators that happen to dislike approaching ants are more likely to survive and reproduce, and their genes get passed on; ultimately instinctive ant aversion dominates the population, and those that lack the trait are quickly weeded out by the ants themselves.

A GLORIOUS MESS

THE COMPLEXITY my colleagues and I have discovered in the mimicry system of *Myrmarachne* serves as a cautionary tale: the tangled principles at work here almost certainly apply to other cases of mimicry. And we still have much to learn. Scientists have tended to view mimicry in terms of its being an adaptation to selective pressure from a single predator using a single sense: vision. (Because humans are so dependent on vision, this sense tends to be the one researchers focus on.) But we now know from *Myrmarachne* that multiple predators shape a mimic species: my own work has shown that ordinary jumping spiders and mantises are influential in this regard; birds, lizards and frogs probably are, too. And studies of other creatures hint that mimicry can involve smell and sound, among other senses. For example, a palatable species of tiger moth mimics the acoustic signals of a noxious one to avoid predation by echolocating bats. And some butterfly species copy the chemical signals emitted by ants to enter their well-defended nests, where the butterflies deposit their eggs for safekeeping.

Excitingly, scientists now have the technology to probe the sensory experiences of other species. High-frequency recording devices allow researchers to visualize noises above our own hearing threshold—including those emitted by tiger moths and bats; mass spectrometry lets them see the hydrocarbon profiles of ants and their mimics, providing a picture of their chemical interactions. Applying these techniques to the study of mimicry and other natural phenomena will no doubt expose more of the spectacular solutions and trade-offs that have evolved in the eternal arms race between predators and prey. SA

Ximena Nelson is a lecturer in animal behavior at the University of Canterbury in Christchurch, New Zealand. Her research focuses on animal communication and cognition, particularly in jumping spiders and birds.

MORE TO EXPLORE

Specialized Exploitation of Ants (*Hymenoptera: Formicidae*) by Spiders (*Araneae*). R. R. Jackson and X. J. Nelson in *Myrmecological News,* Vol. 17, pages 33–49; 2012.

Locomotory Mimicry in Ant-Like Spiders. Ximena J. Nelson and Ashley Card in *Behavioral Ecology,* Vol. 27, No. 3, pages 700–707; 2016.

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TERMITES BUILT this cathedral-shaped mound in Litchfield National Park in Australia. Made from soil, saliva and dung, such structures can stand more than five meters (16 feet) high.

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the evolution of architecture

The homes that animals build are just as much a product of evolution as the creatures themselves

By Rob Dunn

IN BRIEF

Birds, mammals, fish, social insects and many other animals construct a wide variety of intricate nests and homes. Researchers have long known that genes and behaviors must have evolved to enable creatures to build these structures. **Only in recent decades** have scientists started to reveal the genetics of animal architecture, the physics that holds their creations together and the surprisingly simple behavioral rules that allow many small-brained critters to build empires. **One day we may be able** to create computer programs that follow the same architectural rules as social insects to design more efficient cities.

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I HAVE LONG BEEN FASCINATED BY THE HOMES THAT ANIMALS CONSTRUCT. OVER the years I have contemplated the nests of hundreds of different species—including ants, termites, wasps, birds, fish and mice—by poking and prodding nests in the wild, manipulating them in the laboratory and reviewing the work of other scientists. I have dug holes meters deep, trying to find the bottoms of ant nests. I have snorkeled over bluegill fish, watching them excavate and tend to their dish-shaped nests. As a boy, I even tried to swim up into a beaver lodge.

In studying these homes, I have encountered an astonishing diversity of forms. Some nests are long, straight tunnels. Some are branching labyrinths. Others spin in wild helices or take on elaborate fractal forms. But what I find most remarkable about each construction is that it evolved. Each type of nest is just as integral a part of the species and individuals that made it as the animals' limbs, eye color, skin covering and genes. Indeed, the instructions to build nests must be, at least in part, inscribed in the genes of the animal kingdom's architects.

Only now are biologists finally beginning to understand how such architecture evolved. Recent research has started to pinpoint some of the genes responsible for nest-building behavior, reveal the physics underlying the shapes of different animals' nests and even explain the way that some puny-brained critters work together to construct entire metropolises. Like many good stories, this one begins in a garage.

A HOUSE FOR A MOUSE

IN 2003 HOPI E. HOEKSTRA was a young scientist, then at the University of California, San Diego, trying to uncover the links between genes and the behavior of mice. She already knew that different kinds of mice build differently shaped tunnels. Jesse N. Weber, then a student in Hoekstra's lab, began to wonder if he and Hoekstra could find the genes associated with building one type of nest rather than another.

Weber's first task was to craft indoor enclosures that were large enough and held enough dirt to entice mice to dig tunnels. He improvised, building cages out of plywood, nails, playground sand, and other inexpensive and easily accessible materials. Because no lab space was available for the project, he built the cages in the garage attached to Hoekstra's home. The results were ugly but effective: a series of sheds held together by duct tape and ambition.

Hoekstra was already studying field mice in the genus *Peromyscus,* so Weber decided to fill these cages with two *Peromyscus* species: oldfield mice (*P. polionotus*) and deer mice (*P. maniculatus*). Deer mice, which live across much of North America (except the far Southeast), dig a single, short tunnel, whereas oldfield mice, which live exclusively in the far Southeast, dig a long tunnel with a branching escape route that dead-ends just below the soil surface.

When scientists studying lab mice want to find the gene behind a particular trait, they often mate mice that do have that trait with those that do not and see which of those parents the offspring resemble. If the new generation has the trait, it might just be encoded by a dominant version of a single gene, a bossy allele. This trick—the same one Gregor Mendel used on his pea plants—works best for relatively simple relations between genes and traits. Tunnel building did not seem likely to be a simple trait encoded by one gene, but Weber gave the approach a try, anyway. Oldfield and deer mice do not mate in the wild, but, as they say, what happens in the garage stays in the garage. Weber got the mice to mate; he then allowed the resulting progeny to dig.

The most probable scenario was that the tunnels of the hybrid mice would be a complex amalgam of those built by their parents, the middling mélange of genetic complexity. Instead this first generation of hybrid mice all built long tunnels with escape hatches. In theory, this pattern could result from simple dominance involving as few as two genes: one associated with tunnel length and the other with the escape hatch. Inheritance

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1

2

3

NO PLACE LIKE HOME: A common wasp nest is in early stages of construction (*1*); weaverbirds construct their dwellings from materials such as grass and palm leaves (*2*); green tree ants use silk to stitch leaves into a home (*3*).

of one or two dominant versions of the tunneling gene from an animal's parents would yield long tunnels; likewise for the hatch gene. Only two recessive versions of either gene would result in truncated tubes or no escape hatch. But Weber and Hoekstra thought such simplicity unlikely.

Yet when they crossed the hybrid mice with the deer mice (a backcross), they were surprised to find something akin to what might be expected from simple dominance, at least for escape tunnels. About half the progeny built escape routes, and half did not. Tunnel length, in contrast, varied continuously, suggesting more complexity. In follow-up work, Weber, now a postdoctoral fellow at the University of Texas at Austin, and Hoekstra, now a professor at Harvard University, ultimately identified the particular regions of the mouse genome associated with each attribute. Escape-hatch building is controlled by a group of genes, or even just one gene, on a single chromosome. Tunnel length appears to be governed by several genes scattered among three parts of the genome, which would explain the greater complexity observed in Weber's crosses.

Weber and Hoekstra's work demonstrated that even in smart animals, such as mice, complex behaviors involved in nest construction can be both genetically encoded and a product of evolutionary forces. With this discovery, Weber and Hoekstra pulled a string loose from an enormous ball of yarn. To unravel the rest of the ball, Weber, Hoekstra and other scientists will have to repeat similar experiments for each of the tens of thousands of species that build. Scientists in Russell Fernald's lab at Stanford University are already exploring the genes underlying nest design in cichlid fish in which some species make divot nests and others make mounds. More studies will follow.

The genetics of building in some animals will no doubt prove more complex than in field mice. Some species, such as canaries, learn how to build—or, in the case of bowerbirds, decorate—their constructions by mimicking their parents and peers. Others, such as many social insects, are difficult to breed properly in the lab. But the genetic basis of building is not the only, or even the deepest, mystery surrounding the animal kingdom's architects. There is also the issue of why nests vary so greatly across different species and how to explain their particular and often peculiar shapes.

TOWERING TERMITES

THE NESTS OF *PEROMYSCUS* MICE and most mammals are fairly simple; they do not vary immensely from region to region and species to species—an extra tunnel here, a larger chamber there. Even among birds, real variety in nest structure is the exception rather than the rule. Most bird nests are simple cups, bowls or pouches, differing in the subtleties of their shape and components rather than in more fundamental ways. The true animal

PAGE 8 AND THIS PAGE: INGO ARNDT *Nature Picture Library*

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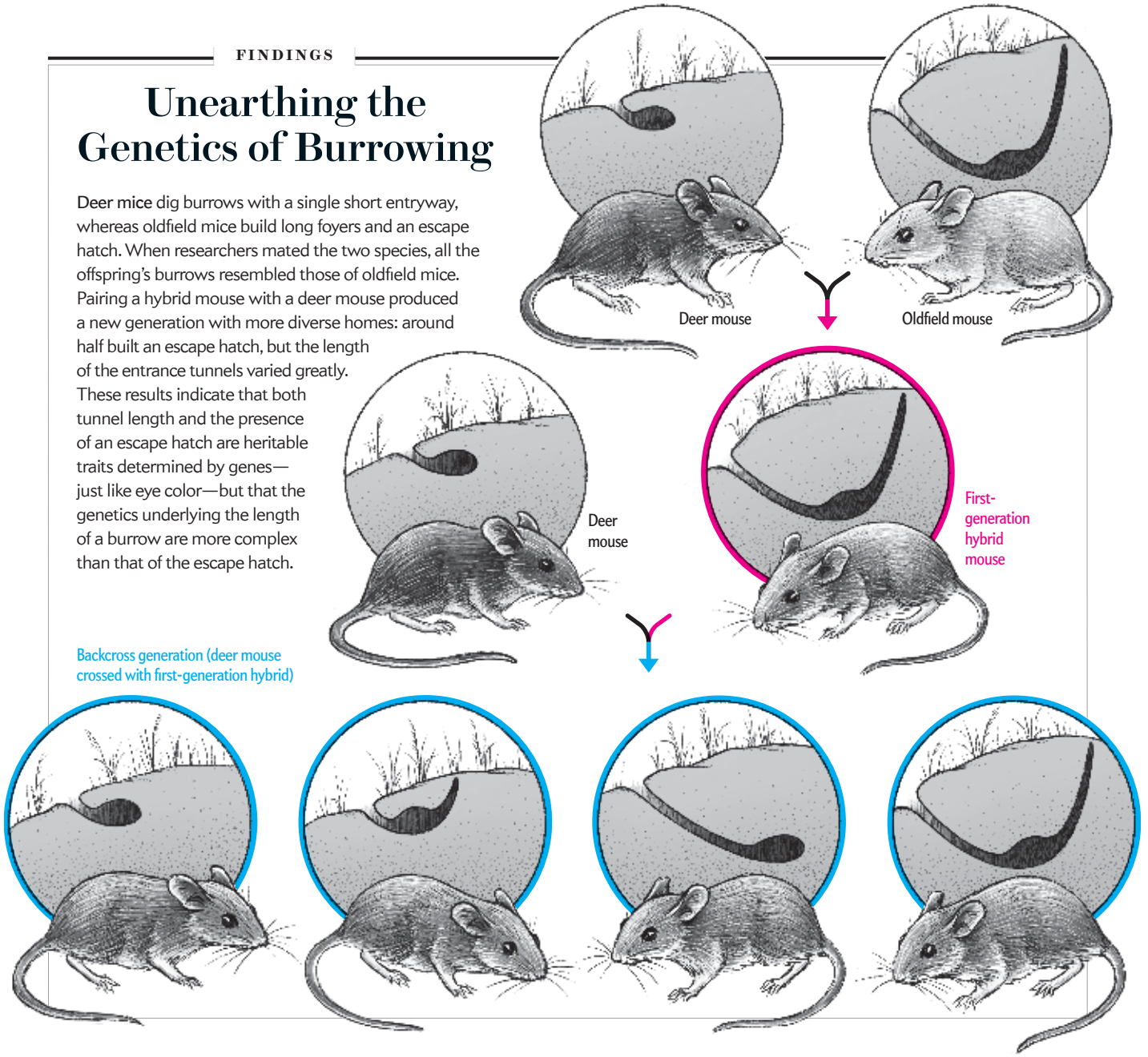
Unearthing the Genetics of Burrowing

Deer mice dig burrows with a single short entryway, whereas oldfield mice build long foyers and an escape hatch. When researchers mated the two species, all the offspring's burrows resembled those of oldfield mice. Pairing a hybrid mouse with a deer mouse produced a new generation with more diverse homes: around half built an escape hatch, but the length of the entrance tunnels varied greatly. These results indicate that both tunnel length and the presence of an escape hatch are heritable traits determined by genes—just like eye color—but that the genetics underlying the length of a burrow are more complex than that of the escape hatch.



masters of architecture are social insects. The beehive, the wasp nest, the ant mound, the termite hill: each of these varies from one species to the next more than the bodies of the insects themselves do. Termite workers nearly always look the same—flaccid abdomens connected to round heads and mandibles—but their nests can look like Rorschach forms, skyscrapers eight meters tall, domes, pyramids and even crumbly balls suspended in trees.

It would be easy to discount this diversity as accidental—the manifestation of a clumsy collective of unknowing beasts. Yet in many cases that have been studied, the features of nests are consistent from one structure to the next within a species. This consistency extends to parts of the nest that appear to have no function, such as vacant chambers. But termites build these puzzling features into their nests over and over again. In recent years scientists have started to uncover the purpose of such chambers.

This architectural puzzle is especially apparent in the nests of *Macrotermes bellicosus* termites, which farm and harvest *Termitomyces* fungi inside their homes. Surrounding these gardens and their millions of attending termites are central towers with pointy, sealed tops. Around these towers sit well-used chambers in which workers, and even the queen, live, along with an outer row of unused chambers. The creatures coat the unused chambers with a hard but porous surface that allows air, but not predators, to pass through.

Judith Korb of the University of Freiburg in Germany has been particularly interested in these features of giant *Macrotermes* mounds. With help from temperature sensors, collaborators and a whole lot of digging, Korb has discovered that the seemingly unusual architectural features of termite nests work like a giant mud lung. During the day the heated air, full of carbon dioxide exhaled by the termites, rises into the center of the nest. There, in the thinnest part of the mound, the hot air and CO_2 diffuse upward. If they did not, the insects would suffocate in their own exhalation. As night comes, cooler, oxygen-rich air

Illustration by Jillian Walters

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diffuses back into the bottom of the nest, in through the empty outer chambers. As it does, it pushes CO_2-laden air out. This big mud lung is adapted to the climate in which the *Macrotermes* termites live. Far from being accidental and useless, the nest's empty chambers allow the termite collective to breathe.

In addition to microclimate control, nests also shield their builders from enemies. Termite nests are as thick as they are because of the threats posed by aardvarks, anteaters, armadillos, echidnas and a small army of other organisms that specialize in eating termites. To protect its young from parasites, a newly identified species known as the bone-house wasp blockades its nest with pungent piles of fearsome ant corpses. Then, of course, there is the option of an escape tunnel. The oldfield mouse lives in the southeastern U.S., where snakes are abundant and diverse. Its escape hatch most likely is an adaptation in response to such serpents. Some tropical ants have recently been shown to keep a pebble near their nest entrance. When army ants approach, they close the nest with their pebble. Other ants defend against army ants by having soldiers with heads just wide enough to plug the entrance. Some birds defend their nests through camouflage, creating inconspicuous nests, such as those of cream-colored coursers, which look like little more than pebbles in the desert sand.

Perhaps the greatest challenge for nature's builders is one that scientists have only begun to consider: excluding deadly organisms too small to see, such as bacteria and microscopic fungi. In the past few years researchers have discovered that some termites build their nests out of their own feces, often mixed with other materials. In these fecal bricks, some termites plant a garden of *Actinobacteria,* which helps to battle deadly fungi by producing antifungal compounds. Leafcutter ants cultivate similarly defensive bacteria on their bodies.

COMMUNAL CONSTRUCTION

ONCE WE UNDERSTAND the environmental conditions and threats that have favored a particular nest type and the genes associated with that type, we will still need to figure out how those genes guide an animal through the nest-building process. In the case of social insects, it is tempting to think that the colony merely obeys a ruler—some fat-bodied queen with a scheme. But there is no master plan, just the unconscious actions of many individuals following simple rules that, when acted out in concert, can produce the enormous nests of termites, the cavernous lairs of ants and even the intricate honeycombs of bees.

Over the past 15 years scientists have developed increasingly sophisticated mathematical models that mimic how such simple rules culminate in the construction of termite homes. The models assume that the building blocks the termites use have a pheromone in them that triggers additional building but eventually wears off. One worker puts down a block, and another, tempted by the first block's odor, follows suit. The process continues until two curving walls come together to form a roof. The act of building walls and roofs was easy to simulate. But what about the precise arrangement of those walls to form tunnels and rooms?

Here, too, simple rules seem to be at the heart of the complexity, although the story continues to emerge. Regarding, for example, the royal chamber—the oval room that surrounds the queen termite—it appears that the queen emits a pheromone that prevents workers from building walls close around her. The workers, as a result, build a wall a consistent distance from the queen. Rather than imagining they have discovered exactly how these termites and wasps build their homes, scientists believe they have gleaned the minimum number of rules necessary to produce something as sophisticated as a nest. The answer is very few—a handful encoded in the insects' genes and tiny brains.

In contrast to the diverse, genetically encoded, often cooperatively constructed nests of rodents and social insects, the nests of wild primates are humble. Chimpanzees and gorillas break off leaves to make beds; one of my colleagues has slept in these beds and describes them as "comfortable" but only relative to their absence. Our ancestors are unlikely to have been very different until, at some point, our kind began to build in earnest. Using language to coordinate their efforts, our ancestors built homes out of what was at hand: sticks, mud, grass and leaves. No genes encoded the precise designs of these shelters. Look at images of indigenous houses around the world, and you will see that, to a large extent, form follows function and necessity. In cold regions, walls are made thicker. In warm regions, walls are not built at all. You will see traditional houses that mimic termite nests, ant tunnels and even, in the cold, the sod thatch of bumblebees.

The more time we invested in considering how to build houses, the more roles houses took on: they have become status symbols, artworks and even markers of culture. Houses in some new Arizona subdivisions now look very similar to those in New York subdivisions because we are conditioned by society to desire the same "good life"—the same house and white picket fence—regardless of where we live, regardless of climate, predators, pathogens or anything else. We have disconnected our architecture from some of the imperatives of the wild.

Recently, though, a different approach to architecture has emerged, a counterbalance to the trend of individually designing each room, each support, each door and garden. The designs of animals, as we now know, emerge from genes that encode simple rules. If termites can use simple rules to produce empires, we, too, might do the same. Some architects are now trying. Scaling up the simple rules used by social insects to human-sized cities requires tremendous computing power, but such power is increasingly a reality. The final challenge is knowing which simple decisions to mimic—in what situations it is best to behave like a termite, an ant or a bee. We are as close to the answers as we have ever been. Yet to watch empires of mud and spit rise out of the ground one mouthful at a time is to realize that the earth's most ancient architectural techniques remain very much a secret. SA

Rob Dunn is a biologist at North Carolina State University and a writer whose articles have appeared in *Natural History, Smithsonian* and *National Geographic,* among other publications.

MORE TO EXPLORE

Discrete Genetic Modules Are Responsible for Complex Burrow Evolution in *Peromyscus* Mice. Jesse N. Weber, Brant K. Peterson and Hopi E. Hoekstra in *Nature,* Vol. 493, pages 402–405; January 17, 2003.

The Evolution of Burrowing Behavior in Deer Mice (Genus *Peromyscus*). Jesse N. Weber and Hopi E. Hoekstra in *Animal Behaviour,* Vol. 77, No. 3, pages 603–609; March 2009.

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THE PROLIFIC AFTERLIFE OF WHALES

On the deep seafloor, the carcasses of the largest mammals give life to unique ecosystems

By Crispin T. S. Little

ON A ROUTINE EXPEDITION IN 1987, OCEANOGRAPHERS IN THE SUBMERSIBLE *ALVIN* WERE MAPPING the typically barren, nutrient-poor seafloor in the Santa Catalina Basin, off the shore of southern California. On the final dive of the trip, the scanning sonar detected a large object on the bottom. Piercing through the abyssal darkness down at 1,240 meters, *Alvin*'s headlights revealed a 20-meter-long whale skeleton partly buried in sediment. On reviewing the dive videotapes, expedition leader Craig Smith and his team saw that the skeleton was probably either a blue or a fin whale. The creature appeared to have been dead for years, but the bones and their surroundings teemed with life—wriggling worms, centimeter-size clams, little snails and limpets, and patches of white microbial mats. The skeleton was a thriving oasis in a vast, desertlike expanse.

Almost a year later Smith, an oceanographer at the University of Hawaii at Manoa, returned for a proper study of the skeleton site. His team described several species previously unknown to science, plus some that had been observed only in unusual environments, such as at deep-sea hydrothermal vents.

Since then, investigators have documented dozens of communities that are supported by sunken whale carcasses and have described more than 400 species that are living in and around them, of which at least 30 have not been seen anywhere else. The research has begun to sketch out a picture of how these surprising whale-fall communities work and how they have evolved.

The first hint that dead whales could host specialized animal communities came as early as 1854, when a zoologist described a new species of centimeter-size mussel extracted from burrows in floating whale blubber collected off the Cape of Good Hope in South Africa. When industrial deep-sea trawling began in the 20th century, researchers learned that such dependence on dead whales was not a freak occurrence. From the 1960s onward an increasing number of whale skulls and other bones with attached specimens of new mollusk species were recovered from nets around Scotland, Ireland, Iceland and particularly the Chatham Rise to the east of New Zealand. One bone specimen trawled off the South African coast in 1964 was covered with the same small mussel first seen in 1854 in roughly the same area.

Mussels were not the only new animals found in recovered whale bones: a tiny, previously unknown species of limpet—limpets are snail-like mollusks with conical rather than spiral shells—was described in 1985, soon followed by others. The limpets were named *Osteopelta* because of their association with bones.

But not until Smith's fortuitous discovery in 1987 did the full extent of the ecological novelty of sunken dead whales become clear. The mollusk species his team found were especially interesting. The clams and mussels belonged to groups known to harbor chemosynthetic bacteria. Such bacteria can draw energy from inorganic chemicals, and they sometimes form the basis of entire ecosystems. (The earliest organisms, before life "invented" photosynthesis and introduced oxygen into the biosphere, were chemosynthetic, although they had a different metabolism from that of modern chemosynthetic organisms.) Most of the mollusks were known only from other chemosynthesis-based sites: the mussels from sunken wood and hydrothermal vents; vesicomyid clams from vents and cold seeps, where fluids rich in methane and other hydrocarbons leak onto the seafloor; lucinid clams from seeps and anoxic sediments (seafloor sediments lacking oxygen); and a snail from anoxic sediments.

The similarities led Smith and his co-workers to suggest in 1989 that whale skeletons

IN BRIEF

A single dead whale can nourish a specialized ecosystem that lasts for decades.

Some signs suggest that whale-fall ecosystems have exchanges with other deep-seafloor communities, such as hydrothermal vents.

Species similar to those at whale falls may have depended on dead marine reptiles for hundreds of millions of years.

Illustration by Bernard Lee

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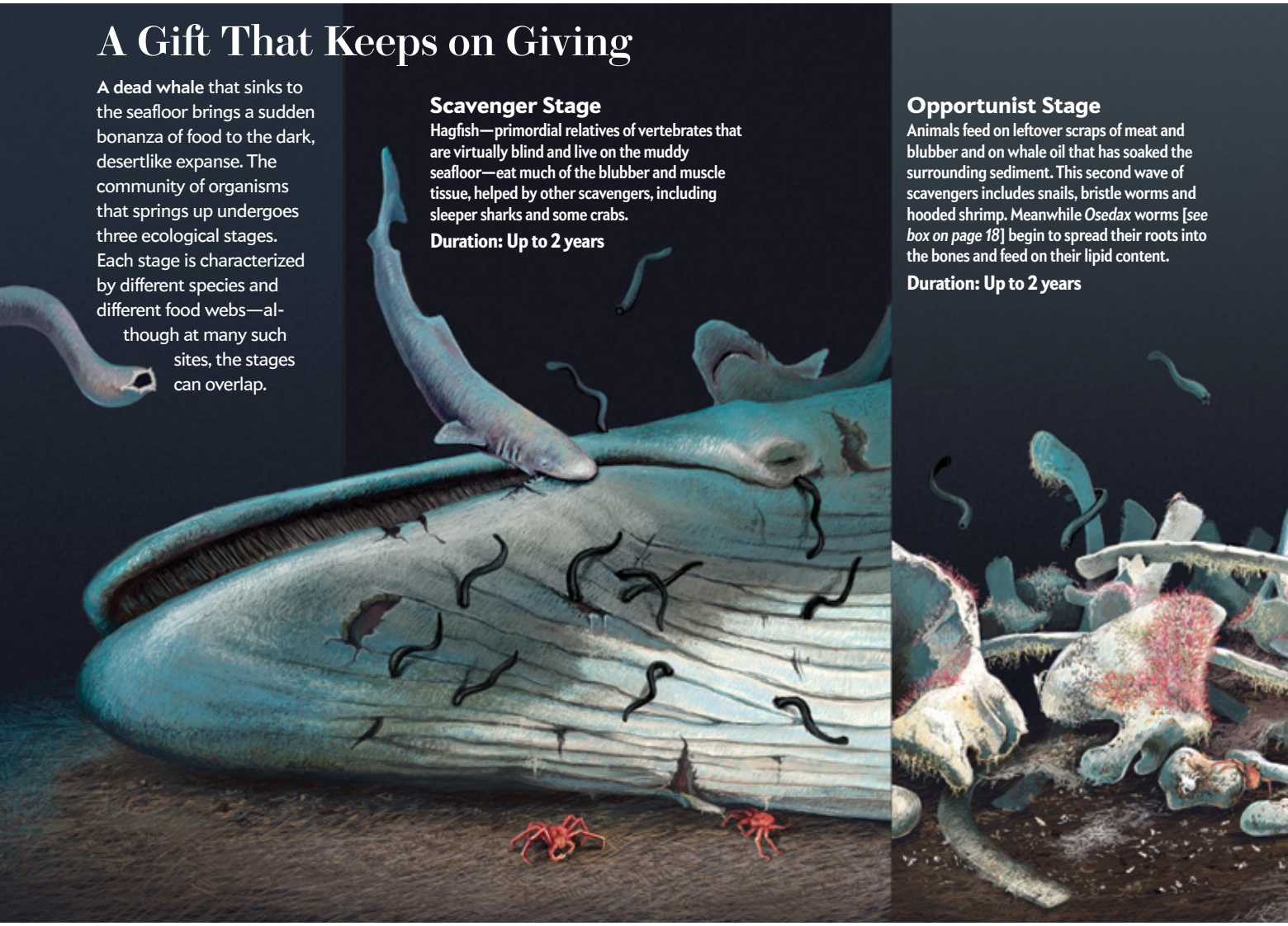
STAGES OF A WHALE-FALL COMMUNITY


A Gift That Keeps on Giving
A dead whale that sinks to the seafloor brings a sudden bonanza of food to the dark, desertlike expanse. The community of organisms that springs up undergoes three ecological stages. Each stage is characterized by different species and different food webs—although at many such sites, the stages can overlap.
Scavenger Stage
Hagfish—primordial relatives of vertebrates that are virtually blind and live on the muddy seafloor—eat much of the blubber and muscle tissue, helped by other scavengers, including sleeper sharks and some crabs.
Duration: Up to 2 years
Opportunist Stage
Animals feed on leftover scraps of meat and blubber and on whale oil that has soaked the surrounding sediment. This second wave of scavengers includes snails, bristle worms and hooded shrimp. Meanwhile Osedax worms [see box on page 18] begin to spread their roots into the bones and feed on their lipid content.
Duration: Up to 2 years

might act as "stepping-stones" for deep-sea animals to spread from one chemosynthetic community to another. Whether creatures can move between communities from one generation to the next or whether species spread on much longer timescales is a question that is still open to this day.

THE MAKING OF AN ECOSYSTEM

TO UNDERSTAND THE WORKINGS and duration of whale-fall communities, Smith and his colleagues set up a logistically tricky—and somewhat smelly—project in 1992. They began to take whales that had washed up on the Californian coast and tow them out sea and then sink them in deep waters with up to 2,700 kilograms of steel ballast to counteract the buoyancy of decomposition gases. (Most whales are negatively buoyant when they die and thus sink rather than get beached.) Next they visited the sunken carcasses at regular intervals using *Alvin* or remotely operated vehicles (ROVs). The researchers sank three gray whales over a period of six years and visited these regularly up until 2000. They also revisited the original skeleton found in 1987 and another discovered in 1995.

Whale falls, they observed, go through three partially overlapping ecological stages. The first, which they called the mobile scavenger stage, starts when the whale carcass arrives on the seafloor. Hordes of hagfish tunnel through the meat, while a few sleeper sharks take larger bites. These scavengers strip away the bulk of the whale soft tissue—blubber, muscle and internal organs—and together consume 40 to 60 kilograms a day (the weight of a small person). Even so, the feast can last up to two years, depending on the size of the whale.

The second stage, referred to as the enrichment opportunist stage, persists for up to two years. During this period high-density, though low-diversity, communities of animals colonize the sediments surrounding the whale carcasses and the newly exposed bones. The animals feed directly on the large amounts of blubber and other scraps of nutritious soft tissue left over by the scavengers. This stage is dominated by polychaetes (bristle worms) and crustaceans.

Finally, once the soft tissue is gone, the whale falls enter the

Jen Christiansen (whale-fall illustrations); Catherine Wilson (species inset illustrations)

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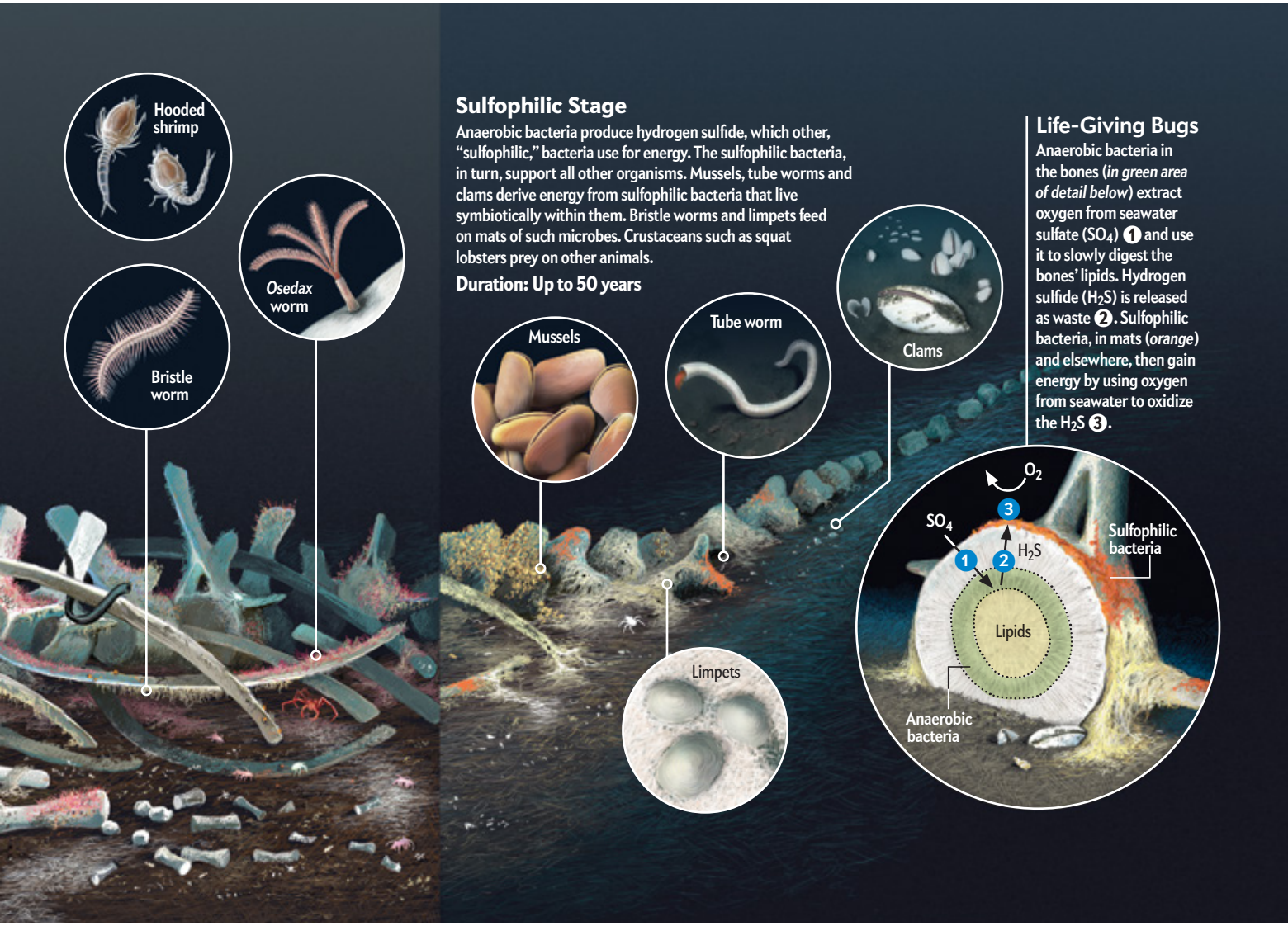
Hooded shrimp
Osedax worm
Bristle worm
Sulfophilic Stage
Anaerobic bacteria produce hydrogen sulfide, which other, "sulfophilic," bacteria use for energy. The sulfophilic bacteria, in turn, support all other organisms. Mussels, tube worms and clams derive energy from sulfophilic bacteria that live symbiotically within them. Bristle worms and limpets feed on mats of such microbes. Crustaceans such as squat lobsters prey on other animals.
Duration: Up to 50 years
Mussels
Tube worm
Clams
Limpets
Life-Giving Bugs
Anaerobic bacteria in the bones (in green area of detail below) extract oxygen from seawater sulfate (SO_4) 1 and use it to slowly digest the bones' lipids. Hydrogen sulfide (H_2S) is released as waste 2. Sulfophilic bacteria, in mats (orange) and elsewhere, then gain energy by using oxygen from seawater to oxidize the H_2S 3.
O_2
3
SO_4
1
2
H_2S
Sulfophilic bacteria
Lipids
Anaerobic bacteria

third, and longest, phase, known as the sulfophilic stage. Specialized bacteria anaerobically break down lipids contained in the bones. Unlike aerobic bacteria, which would use the molecular oxygen (O_2) dissolved in seawater to digest nutrients, these microorganisms use dissolved sulfate (SO_4) as their source of oxygen and release hydrogen sulfide (H_2S) as waste. Animals cannot use this gas directly as a source of energy, and in fact the gas is typically poisonous to them. But certain chemosynthetic bacteria can. They take O_2 from the seawater to oxidize the sulfide, generating energy for growth. Animals can then either exploit such bacteria symbiotically (as do mussels and vesicomyid and lucinid clams) or feed on them by grazing bacterial mats (as do limpets and snails). For reasons that are not yet well understood, whale bones are extremely rich in lipids—a 40-ton whale carcass may contain 2,000 to 3,000 kilograms—and their decomposition is a slow process. As a consequence, for a large whale the sulfophilic stage can last up to 50 years, even perhaps a century.

Using these data—together with their estimate that around 69,000 great whales die every year—Smith and his co-workers guessed that there might be 690,000 skeletons of the nine largest whale species rotting in the world's oceans at any one time. (Of course, before industrial whaling caused a dramatic crash in large-whale populations during the past two centuries, considerably more whale falls would have been active, perhaps as many as six times more.) The average distance from one whale to the next would then be just 12 kilometers; along the migration route of gray whales, the average distance may be as short as five kilometers. Such spacing may be close enough for larvae to disperse from one site to another, which the team saw as further support for their stepping-stone model for the dispersal of chemosynthetic organisms between whale falls, hydrothermal vents and cold seeps.

NIGHT CREATURES CALLING

EVER SINCE Smith and his colleagues set up their whale-fall experiment, sinking large dead whales has proved quite popular; other groups, including those based in Sweden, Japan and Monterey, Calif., have been conducting similar experiments. Other whale skeletons have been found by chance in various

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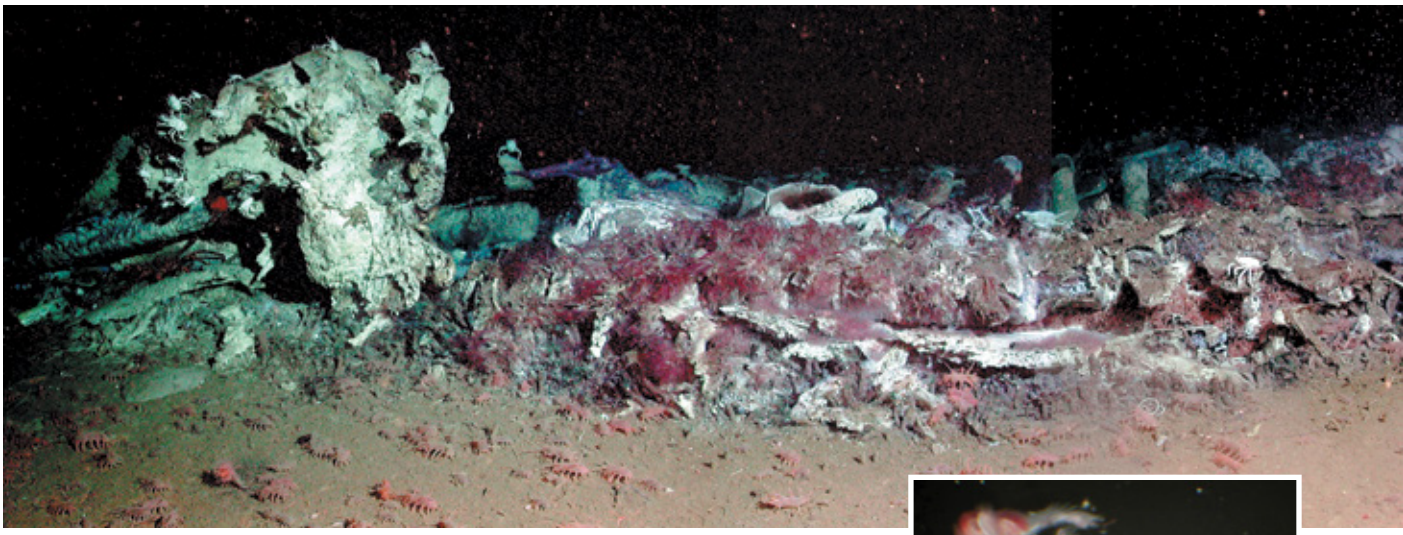

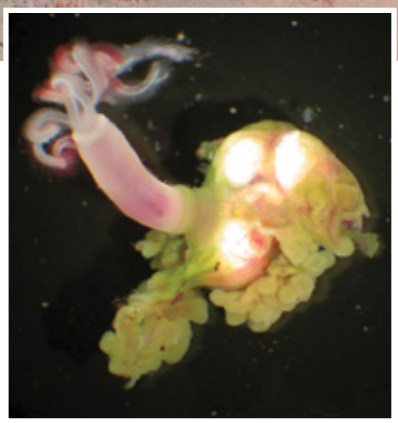

LYING 2,891 METERS DEEP in Monterey Bay, Calif., this 10-meter-long gray whale provides nourishment for a thriving community, including scavenging sea cucumbers (*Scotoplanes globosa*, crawling on foreground) and bone-eating worms (*Osedax rubiplumus*, on bones). The three shots that make up this montage were taken in 2002 by an undersea robot operated by the Monterey Bay Aquarium Research Institute; some of the bones seen here have since completely decomposed.

***OSEDAX* WORMS** (Latin for "bone devourer") grow "roots" in the bones of dead whales (and the bones of other creatures on the ocean floor), which they slowly consume. This *Osedax frankpressi* has been removed from a whale bone to show its root system (*green*) and ovaries (*white*); typically only the one-centimeter-long body (*pink*) and its plumes would be visible. At least five different species of *Osedax* have been discovered so far.

deepwater sites, for example, in the waters around Antarctica, Japan and in Monterey Bay. The newer studies have confirmed that a consistent group of organisms depends on whale falls throughout the world. But the stages seen in the Santa Catalina skeletons are not as apparent elsewhere.

One reason for the discrepancy may be that the experimental sites selected by the Smith team are relatively oxygen-poor, leading to reduced decomposition rates. Another reason might be the activities of the extraordinary worm *Osedax* (Latin for "bone devourer"). This small animal—one centimeter or less in length—was first described in 2004 from a Monterey Bay whale and later found at the experimental sites in Sweden and Japan. Since then, researchers have found the worm at whale falls in all the world's oceans.

Osedax has little appendages that stick out into the water column for gas exchange but can be retracted into a mucous tube if disturbed. The animal then looks like a blob of mucus adhering to the bone surface. Just like certain intestinal parasites, *Osedax* has no digestive tract at all as an adult—no mouth, stomach or anus. But uniquely, it uses green, fleshy "roots" to tunnel into exposed whale bones, presumably to obtain lipids or proteins, or both, for symbiotic bacteria contained within its roots. (The worm's reproductive strategy is also unusual. The adults in all but one species are female, but each carries in its body dozens of tiny males that never pass the larval stage—and whose only role, it seems, is to produce sperm.)

Osedax is closely related to the giant tube worms that live at many vent and seep communities. Genetic evidence suggests that it is around 108 million years old, much older than the vesicomyid clams and whales.

The tunneling activity of *Osedax* rapidly destroys the exposed whale bones, which likely speeds up the sulfophilic stage for an infested skeleton, thus affecting its entire habitat. The finding could mean that many whale falls are active on the seafloor for less time than was originally thought. This time reduction poses a challenge to the stepping-stone hypothesis because fewer active whale falls should make it more difficult for animals (or their larvae) to get from one chemosynthetic site to another.

BONES OF CONTENTION

WHEREAS VENTS and cold seeps have been around since the early earth—and vents in particular may be where life got started in the first place—the appearance of whales is, of course, relatively recent. A natural question is when and how have ecosystems evolved that seem to depend on whale carcasses for their existence, which in turn should help clarify their connection to other deep-sea communities. The obvious place to look is in the fossil record.

Although many fossil whales have been found over the past 150 years, it was only in 1992 that the first ancient whale-fall communities were recognized, in Washington State rocks from the Oligocene (34 million to 23 million years ago). Intense interest in these bizarre communities has since turned up more examples. Among them are some fossils from the Miocene (23 million to five million years ago) found in California and in three sites in Japan—including two that I have worked on with my colleague Kazutaka Amano of the Joetsu University of Education. All these ancient whale-fall communities are recognized as such by the presence of mollusk fossils belonging to groups that host chemosynthet-

COURTESY OF MBARI (*whale fall montage*); COURTESY OF GREG ROUSE (*Osedax worm*)

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Fossil Relatives

Various fossil whales show signs of having sustained communities similar to those of modern whale falls—including many of the invertebrates that depend on symbiotic sulfide-oxidizing bacteria. One specimen from Middle Miocene (about 12 million years ago) rocks on Hokkaido Island, Japan, was surrounded by several shells of mollusks, including snails of the genus *Provanna* (spiral shells at the top, both about half a centimeter tall), a vesicomyid clam (*Adulomya chitanii*, 4 cm) and a mussel (*Adipicola*, 2 cm). These fossils help researchers understand the origin of whale-fall communities.

COURTESY OF KAZUTAKA AMANO

ic bacteria or graze on microbial mats at chemosynthetic sites.

In 2006 Steffen Kiel, then at the University of Leeds in England, and Jim Goedert of Seattle's Burke Museum of Natural History and Culture pointed out that the earliest whale-fall communities from the late Eocene and the Oligocene were dominated by clams that also occur in nonchemosynthetic habitats; the chemosynthetic mollusks that characterize modern whale falls in the sulfophilic stage do not show up until the Miocene fossils. The researchers concluded that the early whales were not yet large enough to host sulfophilic communities. Recently, however, a small Miocene whale skeleton was found in cliffs on a Californian island that had associated vesicomyid clams. This discovery suggests that it is not so much a whale's size that matters to the chemosynthetic mollusks. Instead the relative lipid content in whale bones probably increased over the past 20 million years or so, perhaps because it enhanced survival as whales moved into open-ocean environments.

In fact, ever since the discovery of whale-fall communities, researchers have suspected that similar communities may have existed even earlier than the first whales, in the sunken carcasses of ancient marine reptiles, among them plesiosaurs, ichthyosaurs and mosasaurs. These reptiles were among the dominant predators of the Mesozoic oceans. (The Mesozoic, the geologic era that stretches from 251 million to 65 million years ago, comprises the Triassic, the Jurassic and the Cretaceous and thus the entire time when the dinosaurs ruled on land.) This idea received a strong boost in 1994 with the description of a single fossil specimen of the limpet *Osteopelta* from a turtle bone in Eocene sediments from New Zealand. Although the Eocene is more recent than the Mesozoic, the discovery demonstrated that whale-fall limpets were also able to live on reptile bones and thus perhaps on the extinct Mesozoic marine reptiles as well.

Then, in 2008, a research group from Japan and Poland reported the discovery of bones of two plesiosaur skeletons originally around 10 meters long with associated provannid snail specimens from upper Cretaceous rocks in Japan. Because provannids are only known from chemosynthetic sites, the scientists suggested that the sunken plesiosaurs were able to support a community comparable to the sulfophilic stage of modern whale falls. But these reptiles went extinct 65 million years ago along with the dinosaurs. That is more than 20 million years before whales evolved, suggesting that there may have been a repeated evolution of specialized communities of animals dependent on large vertebrate carcasses sinking to the seafloor.

The Japanese and Polish group showed convincingly that the plesiosaur bones looked internally very like modern whale bones, with lots of marrow space that would have contained lipids in life. Whether the bones were in fact rich in lipids will not be easy to determine, however. On the other hand, it seems that many groups of animals present in whale-fall sulfophilic communities were already present in seep, wood-fall and probably vent communities and that they avidly exploited the newly evolved chemosynthetic habitat when whales evolved.

The fossil record of whale falls remains rather scant, with data coming from Japan, Italy and the Western coast of the U.S. Although the lack of a skeleton makes it unlikely that direct evidence of *Osedax* will be found, the borings it makes in whale bones may be recorded in fossils. Recent fossil evidence of *Osedax* has been found as borings in the bones of whales, in Pliocene rocks from Italy, in Oligocene bird bones from Washington State, and in Cretaceous plesiosaur and marine turtle bones. This evidence shows that *Osedax* evolved at least 100 million years ago and made use of a wide range of vertebrate bones to live on before the whales appeared.

The global distribution of modern whale-fall communities is also still poorly characterized. So far relatively few whale carcasses have been found, and we know little about several areas that have large whale populations, such as the Southern Ocean. More finds, both active and fossil, will be necessary to reveal whether the ecology and evolutionary history of whale falls are truly linked to those of reptile falls and how both types of ecosystems relate to the other deep-sea chemosynthetic communities. SA

Crispin T. S. Little is a senior lecturer in paleontology at the University of Leeds in England. He has been working for the past 16 years on the macroevolutionary history of animal communities found at hydrothermal vents, hydrocarbon seeps and whale falls. On a 2008 oceanographic cruise he achieved a long-standing personal goal of diving in the *Alvin* submersible to active vents 2.5 kilometers deep on the Pacific seafloor.

MORE TO EXPLORE

The Mammals That Conquered the Seas. Kate Wong in *Scientific American*, Vol. 286, No. 5, pages 70–79; May 2002.

Expanding the Limits of Life. Alexander S. Bradley in *Scientific American*, Vol. 301, No. 6, pages 62–67; December 2009.

Whale-Fall Ecosystems: Recent Insights into Ecology, Paleoecology, and Evolution. Craig R. Smith et al. in *Annual Review of Marine Science*, Vol. 7, pages 571–596; 2015.

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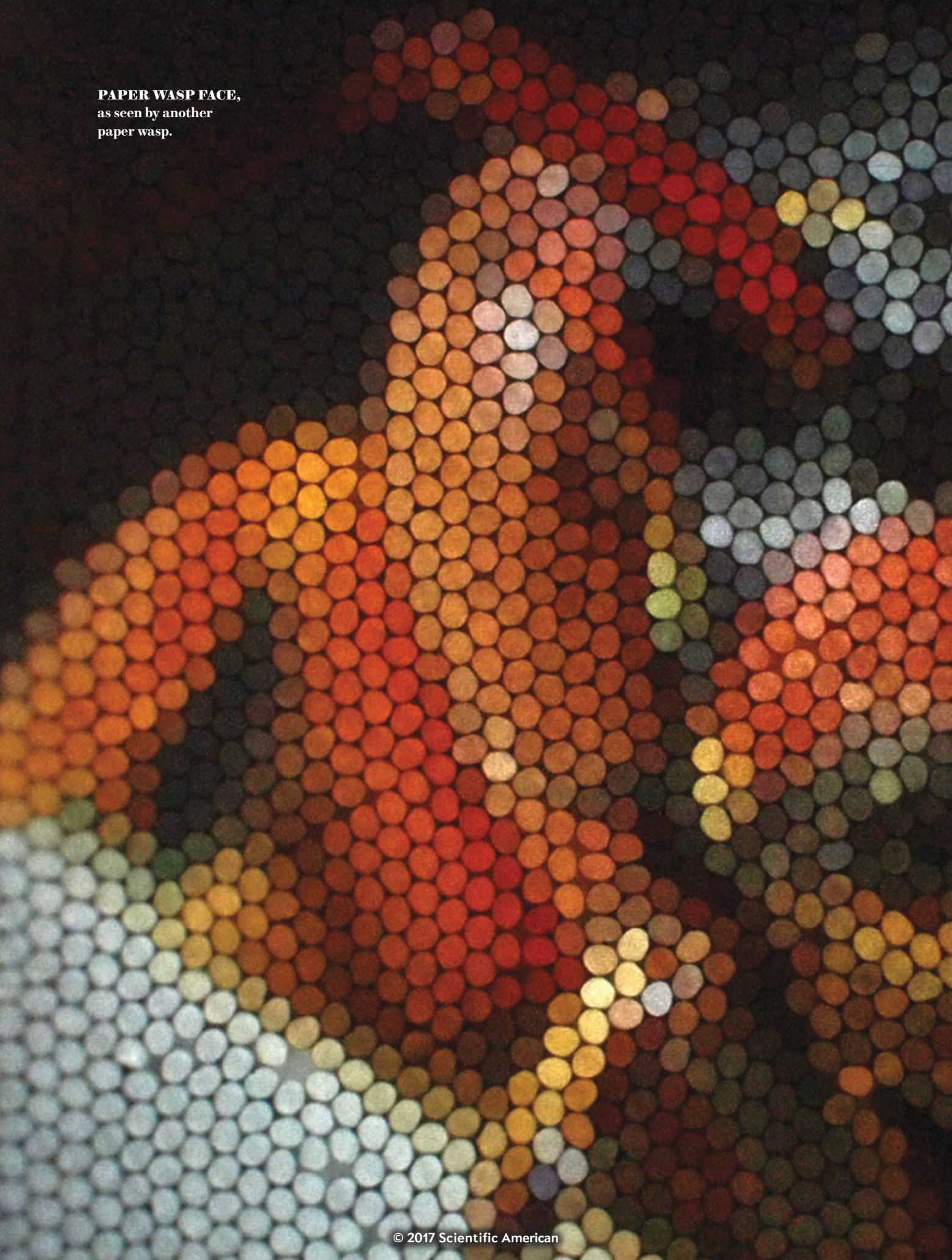

PAPER WASP FACE, as seen by another paper wasp.

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GOOD WITH FACES

Conventional wisdom holds that the ability to recognize faces requires a complex mammalian brain. But some insects are quite adept at this task

By Elizabeth A. Tibbetts and Adrian G. Dyer

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THE WASPS AND BEES BUZZING AROUND YOUR GARDEN MIGHT SEEM like simple-minded creatures. They build nests, forage for nectar, raise their young and then die, their lives typically playing out over the course of a single year or less. Some of these species rival humans and other primates in at least one intellectual skill, however: they recognize the individual faces of their peers. More specifically, members of a species of paper wasp can perceive and memorize one another's unique facial markings and are able to use this information to distinguish individuals during subsequent interactions, much as humans navigate their social environment by learning and remembering the faces of family, friends and colleagues. Further, even certain insects that do not normally memorize faces in the wild can be trained to do so—and can at times even learn to tell human faces apart.

A popular theory of intelligence holds that the exceptionally large human brain evolved to cope with the challenges posed by having to learn and remember many individuals in complex societies. But the discovery that creatures with a brain less than 0.01 percent as large as our own can also identify individuals is forcing scientists to consider how this startling ability evolved and which features of insect brains make facial recognition possible. The answer to the last question, in particular, could help software designers to improve facial-recognition software.

A FORTUITOUS DISCOVERY

AS IS OFTEN THE WAY with scientific discoveries, the revelation that wasps see one another as individuals resulted from a lucky accident. As a young graduate student in 2001, one of us (Tibbetts) was working on a project focused on detailing the social lives of *Polistes fuscatus* paper wasps. The project involved painting colored dots on their backs, then videotaping colonies and tracking the interactions among the insects. One day Tibbetts accidentally videotaped a colony with two unmarked wasps. The data would be useless unless she could figure out a way to differentiate between the two insects. As she watched the tape, she suddenly realized that she could tell the unmarked wasps apart by looking at the yellow, brown and black stripes and spots that make up their natural facial markings. Could wasps, she wondered, do the same?

Tibbetts couldn't resist checking. She spent the next few days documenting the fantastic diversity of facial patterns in wasps and then tested whether the creatures could use these patterns as a guide to recognizing individuals. Using an extremely high-tech method—applying modeling paint with

IN BRIEF

Until recently, scientists thought that the ability to recognize individual faces required a large mammalian brain.

But studies of paper wasps and honeybees have shown some small-brained insects can manage this feat, too.

These insects may use a face-processing mechanism that is similar to the ones humans use to tell faces apart.

This discovery could aid software developers in their efforts to enhance face-recognition software.

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toothpicks—she changed a wasp's facial features and then observed the social consequences. Aggression is rare in wasp colonies, so if the wasp was treated more aggressively by nest mates after the makeover, the behavior shift would be proof that wasps pay attention to faces. As a control, she also applied paint to some insects without changing their appearances to rule out the possibility that the wasps were reacting to some aspect of the paint other than its visual effect. She found that the nest mates displayed far more aggression toward the visibly altered wasps than to the control subjects; for the control wasps, interactions with their nest mates proceeded in a business-as-usual fashion. The results showed that wasps do indeed use variation in facial patterns for individual recognition.

Tibbetts was amazed. To appreciate just how astonishing this finding was, consider how humans recognize faces. First, we must perceive a specific arrangement of unique facial features—such as nose, mouth, eyes and ears—and, in our mind, link the arrangement to more abstract information about the person, such as that he or she is our boss or our neighbor. Then we need to quickly recall that pairing each time we see that particular individual.

Interestingly, we learn faces faster and more accurately than we grasp many other types of complex visual information. For instance: if you go to a party, you can quickly memorize the faces of the attendees without any great effort. It would take substantially more time and effort to learn multiple unique, but visually similar complex patterns such as those used in Chinese script. Both faces and Chinese script are composed of multiple elements that come together into a larger whole, but we are better at learning faces than Chinese script because evolution has furnished us with brain adaptations specifically for learning faces. Indeed, in the human brain a region called the fusiform face area is dedicated to face processing. This processing mechanism is so highly specialized that it fails us if an image is simply turned upside down. Likewise, even small modifications to critical regions of a face, such as the eyes, can hamper our ability to recognize a familiar visage.

Although humans as a species excel at face learning, approximately 2 percent of us have some form of deficit. Most face-learning deficits are thought to be hereditary, although they can also emerge in adulthood after injury to the fusiform face area. Given the importance of social recognition in human societies, such disorders can be debilitating. In some extreme cases, people may even have trouble recognizing their spouses and their children, likening the task to trying to learn the identity of different rocks in the garden. In addition, the impaired social development seen in individuals with disorders such as autism may stem at least in part from face-processing deficits.

Given the importance of specialization to human face learning, Tibbetts pondered whether paper wasps could have independently evolved a similar specialization or whether they instead process faces in a different way. To find the answer, she first needed a reliable method for training wasps to attend to images she deemed "correct" while bypassing incorrect ones. Researchers typically train social insects such as honeybees to perform certain tasks by rewarding them with sugar when they make correct choices. Honeybees are eager to work for sugar because collecting food to share with nest mates is one of their primary jobs. Wasps, however, can survive for weeks without eating, so initial efforts to train them using sugar rewards failed. Tibbetts and her then graduate student Michael Sheehan, now at Cornell University, eventually found that they could train the creatures to go to the correct image in a choice between two by delivering a small electric shock to the wasps when they selected an incorrect image.

With the new training technique, wasps learned to differentiate between respective pairs of five different types of images: normal wasp face images, simple black-and-white geometric patterns, whole caterpillars (the wasps' natural prey), wasp face images with the antennae digitally removed, or scrambled wasp face images. The wasps rapidly and accurately learned to select specific normal faces within only 20 trials but had greater difficulty learning to discriminate among images in the other four pairings. Most strikingly, simply removing the antennae from a wasp face image or rearranging the face components dramatically reduced their impressive face-learning capacity.

The difference in the wasps' ability to learn normal face images versus antennaeless ones provides very strong evidence that wasps have neural systems specialized for wasp face learning. Antennaeless faces are composed of the same colors and patterns as normal faces, but the wasp visual system does not reliably pro-

ILLUSION

Face-Off

The Margaret Thatcher illusion, developed by Peter Thompson of the University of York in England, reveals that face processing in humans is highly specialized. We have trouble recognizing a familiar face when an image is turned upside down and when critical features, such as the eyes and mouth, are inverted. Insects that can learn faces also falter when shown modified images, but whether they process faces just as we do remains to be tested.

FROM "MARGARET THATCHER: A NEW ILLUSION," BY PETER THOMPSON, IN *PERCEPTION*, VOL. 9, NO. 4; 1980; BETTMANN/GETTY IMAGES (*Thatcher*)

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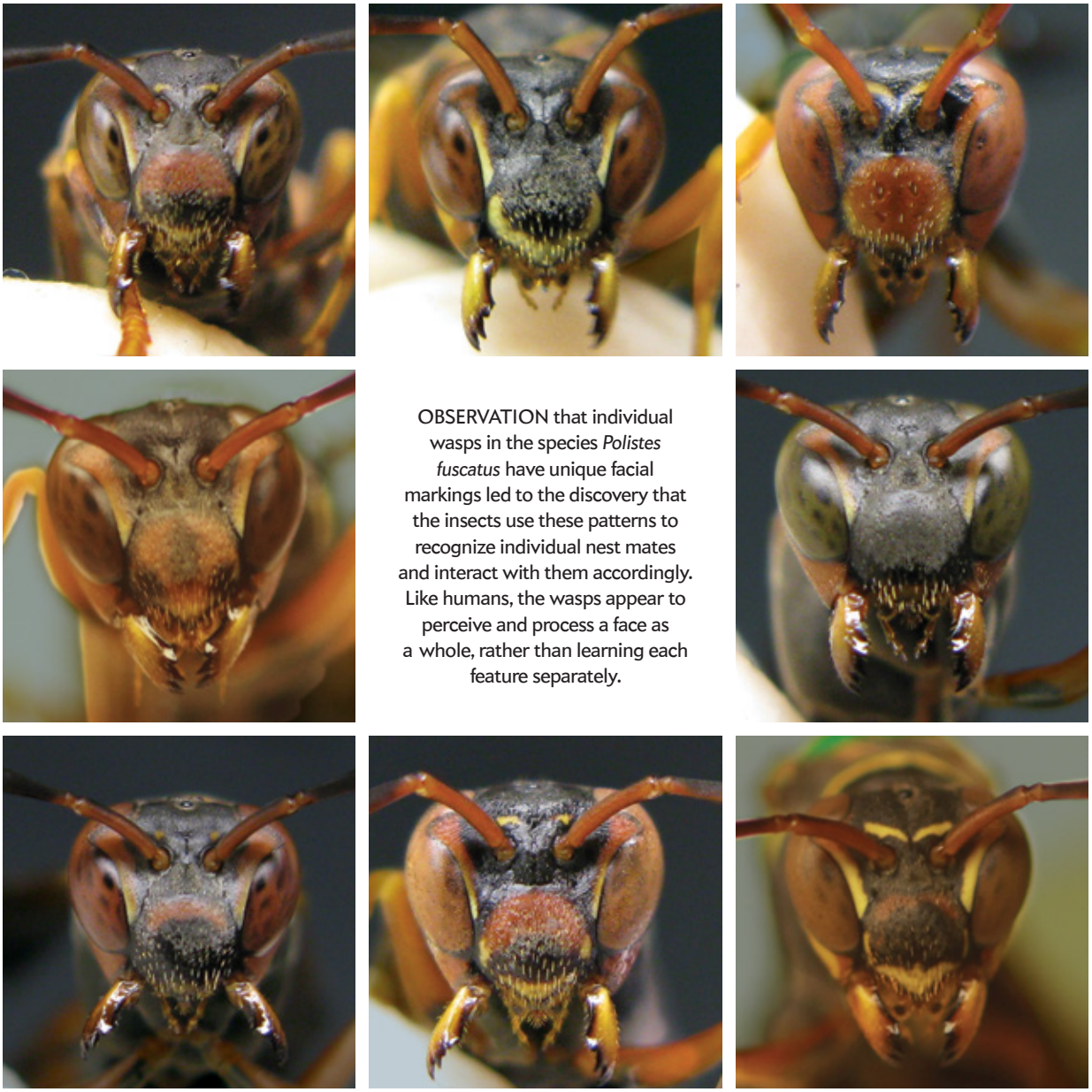

OBSERVATION that individual wasps in the species *Polistes fuscatus* have unique facial markings led to the discovery that the insects use these patterns to recognize individual nest mates and interact with them accordingly. Like humans, the wasps appear to perceive and process a face as a whole, rather than learning each feature separately.

cess and recognize the altered image as a face. The effect of antennae removal on learning indicates that wasps, like people, perceive faces through some kind of holistic processing mechanism. That is, instead of learning each facial feature separately, element by element, the wasp perceives and processes a face as a whole. Thus, for proper learning to occur, the elements must be intact and correctly arranged. The effect of antennae removal on the wasps' ability to learn faces parallels the way human face learning falters when an image of a face is upside down, image brightness is inverted or facial features are scrambled.

The occurrence of face specialization in both humans and wasps suggests that this mechanism could be more widespread in the animal kingdom than initially thought, evolving when social conditions favor it. In the case of *P. fuscatus,* nests are started by groups of queens that work together to survive. But the queens also compete with one another for reproductive dominance. In such situations, it probably pays for cooperating queens to be able to recognize one another and remember how each individual ranks in the dominance hierarchy, hence the evolution of face specialization in this species. By the same token, the face-specialization mechanism should not be present in animals that do not usually need to differentiate individuals.

To test this hypothesis, Tibbetts and Sheehan measured face learning in a close relative of *P. fuscatus—Polistes metricus—* which has a different social structure. *P. metricus* nests are typically founded by a solitary queen. With only one queen reproducing, group members have little to gain socially by being able to recognize individual faces. Tibbetts and Sheehan had previously shown that *P. metricus* wasps do not vary in their facial markings and do not naturally recognize individuals. They then posited

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that *P. metricus* also lacks a special cognitive mechanism for processing faces, unlike the more socially complex *P. fuscatus*. Their findings upheld this supposition.

When given the opportunity, *P. metricus* wasps can learn faces, but it is difficult for them, and they learn faces only about as quickly and accurately as other kinds of images. Furthermore, antennae removal has no effect on the speed or accuracy of their face learning, indicating that this species lacks a specialized holistic-type face-processing mechanism. Instead they process faces as they do any other images: as a collection of independently processed features—perhaps like we humans might learn Chinese script.

AFTER A BEE LEARNS THE FRONT AND SIDE VIEW OF A PARTICULAR FACE, IT WILL BE ABLE TO CORRECTLY CHOOSE A PICTURE OF THE SAME FACE ROTATED 30 DEGREES, EVEN IF IT HAS NOT PREVIOUSLY SEEN THIS PARTICULAR IMAGE.

HOW HONEYBEES SEE HUMANS

GIVEN THAT *P. METRICUS* can slowly learn faces when trained to do so, despite lacking a specialized mechanism for this activity, one might wonder whether insects with small brains have some capacity to also learn faces of an entirely different type of creature: humans. Inspired by the early paper wasp findings, one of us (Dyer), who studies how bees process visual information, became interested in figuring out whether these insects could learn to tell people apart. In this study, he trained common honeybees to distinguish a target face from a so-called distractor face, presenting them with human visages from a standard neuroscience test. The faces are similar enough that human subjects typically make some errors in judgment. The bees received sweet-tasting sucrose solution for making correct visits to a target face and bitter quinine solution for incorrectly choosing a distractor face. Although it took a while for them to catch on, the bees learned to reliably discriminate the pair of target and distractor faces over the course of 50 trials. The bees also learned to select a target face from a group of novel human faces.

Other experiments using this training procedure revealed some striking similarities between honeybee and human face-processing strategies. First, although the bees learned faces slowly as compared with *P. fuscatus* wasps and humans, they were able to develop some ability to process faces holistically, even though they are not hardwired to do so, as *P. fuscatus* wasps and humans are. Second, honeybees were able to learn multiple viewpoints of the same face and interpolate based on this information to recognize novel presentations. For example, after a bee learns the front and side view of a particular face, it will be able to correctly choose a picture of the same face rotated 30 degrees, even if it has not previously seen this particular image. The honeybees' ability to learn faces is especially unexpected because honeybee society is far simpler than that of the wasps, consisting of a single queen and a mass of essentially identical workers that do the same tasks. Honeybees do not have distinctive facial markings, and their interactions in the hive often rely on complex pheromonal signals rather than visual cues.

The results suggest that this line of research could be a boon to efforts to develop automatic face-recognition systems. Identifying the same face from different angles is often thought to be a difficult task and is one of the major challenges of machine face recognition. But the tiny brains of these bees are much simpler than primate brains, so once we figure out what processing tricks the bees use for solving such complex problems, we should be able to apply them relatively simply to machine vision to enhance face-recognition software.

Taken together, these studies in insects tell us something fundamental about how face recognition may have evolved. The simple system that *P. metricus* wasps and honeybees have that allows them to learn to recognize faces through experience even though they do not normally distinguish among individuals in their everyday lives may be based on the general pattern-recognition abilities these species use during foraging. It may also function as an intermediate step in the evolution of face specialization. When the forerunners of today's *P. fuscatus* wasps found themselves in a novel social environment in which telling individuals apart aided their survival and reproduction, the wasps could learn to identify individuals. Over time natural selection most likely built on that foundation, changing their brain to produce the face specialization that enhanced the wasps' ability to sort friend from foe quickly and reliably. The intermediate system allowed this adaptation to evolve rapidly: *P. fuscatus* and *P. metricus* are closely related, and their last common ancestor would have had the comparatively primitive face-learning system seen in *P. metricus*. Thus, *P. fuscatus*'s biological adaptation to processing faces efficiently must have evolved recently, after its lineage diverged from that of *P. metricus*.

So the next time you are out in your garden, take a minute to appreciate the resident wasps and bees. There is ever so much more going on in their teensy brains than we could have imagined possible. SA

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MORE TO EXPLORE

Visual Signals of Individual Identity in the Wasp *Polistes fuscatus*. Elizabeth A. Tibbetts in *Proceedings of the Royal Society of London B*, Vol. 269, pages 1423–1428; July 22, 2002.

Individual Recognition: It Is Good to Be Different. Elizabeth A. Tibbetts and James Dale in *Trends in Ecology and Evolution*, Vol. 22, pages 529–537; October 1, 2007.

Insect Brains Use Image Interpolation Mechanisms to Recognise Rotated Objects. Adrian G. Dyer and Quoc C. Vuong in *Plos One*, Vol. 3, No. 12, Article No. e4086; December 31, 2008.

Configural Processing Enables Discrimination and Categorization of Face-like Stimuli in Honeybees. Aurore Avargues-Weber, Geoffrey Portelli, Julie Benard, Adrian G. Dyer and Martin Giurfa in *Journal of Experimental Biology*, Vol. 213, pages 593–601; February 15, 2010.

Specialized Face Learning Is Associated with Individual Recognition in Paper Wasps. Michael J. Sheehan and Elizabeth A. Tibbetts in *Science*, Vol. 334, pages 1272–1275; December 2, 2011.

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BISEXUAL SPECIES

SECRET LIVES OF ANIMALS

Homosexual behavior is surprisingly common in the animal kingdom. It may be adaptive—helping animals to get along, maintain fecundity and protect their young

By Emily V. Driscoll

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TWO PENGUINS NATIVE TO ANTARCTICA MET ONE SPRING DAY IN 1998 IN A tank at the Central Park Zoo in midtown Manhattan. They perched atop stones and took turns diving in and out of the clear water below. They entwined necks, called to each other and mated. They then built a nest together to prepare for an egg. But no egg was forthcoming: Roy and Silo were both male. Robert Gramzay, a keeper at the zoo, watched the chinstrap penguin pair roll a rock into their nest and sit on it, according to newspaper reports. Gramzay found an egg from another pair of penguins that was having difficulty hatching it and slipped it into Roy and Silo's nest. Roy and Silo took turns warming the egg with their blubbery underbellies until, after 34 days, a female chick pecked her way into the world. Roy and Silo kept the gray, fuzzy chick warm and regurgitated food into her tiny, black beak.

Like most animal species, penguins tend to pair with the opposite sex, for the obvious reason. But researchers are finding that same-sex couplings are quite widespread in the animal kingdom. Roy and Silo belong to one of as many as 1,500 species of wild and captive animals that have been observed engaging in homosexual activity. Researchers have seen such same-sex goings-on in both male and female, old and young, and social and solitary creatures and on branches of the evolutionary tree ranging from insects to mammals.

Unlike most humans, however, individual animals generally cannot be classified as gay or straight: an animal that engages in a same-sex flirtation or partnership does not necessarily shun heterosexual encounters. Rather many species seem to have ingrained homosexual tendencies that are a regular part of their society. That is, there are probably no strictly gay critters, just bisexual ones. "Animals don't do sexual identity. They just do sex," says sociologist Eric Anderson, now at the University of Winchester in England.

Nevertheless, the study of homosexual activity in diverse species may elucidate the evolutionary origins of such behavior. Researchers now understand, for example, that animals may engage in same-sex couplings to diffuse social tensions, to better protect their young or to maintain fecundity when opposite-sex partners are unavailable—or simply because it is fun. These observations suggest to some that bisexuality is a natural state among animals, perhaps *Homo sapiens* included, despite the sexual-orientation boundaries most people take for granted. "[In humans] the categories of gay and straight are socially constructed," Anderson says.

What is more, homosexuality among some species, including penguins, appears to be far more common in captivity than in the wild. Captivity, scientists say, may bring out gay behaviors in part because of a scarcity of opposite-sex mates. In addition, an enclosed environment boosts an animal's stress levels, leading to a greater urge to relieve the stress. Some of the same influences may encourage what some researchers call "situational homosexuality" in humans in same-sex settings such as prisons or sports teams.

IN BRIEF

Same-sex couplings are surprisingly widespread in the animal kingdom. Observers have witnessed as many as 1,500 species of wild and captive animals engaging in homosexual activity. **Animals may engage** in homosexual acts to diffuse social tensions, to better protect their young or to maintain fecundity when opposite-sex partners are unavailable—or simply because it is fun. **Homosexuality** among some species appears to be far more common in captivity than in the wild. Captivity may bring out gay behaviors because of a lack of opposite-sex mates and a greater need for stress relief.

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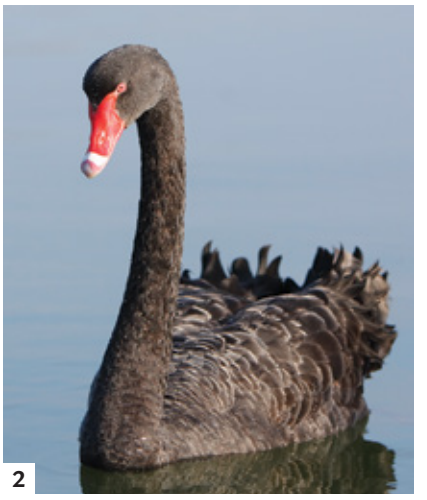

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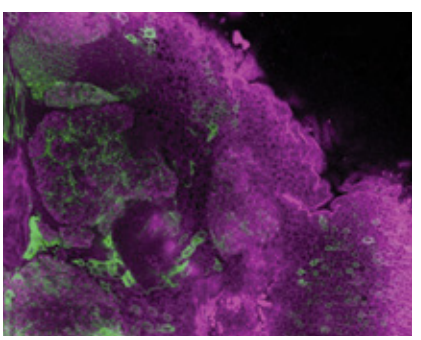
EXAMPLES: Female homosexual encounters among bonobos (*1*) help the apes get along: they resolve conflicts and promote bonding. Up to one quarter of black swan (*2*) families include parents of the same sex.

MAKING PEACE

MODERN STUDIES of animal homosexuality date to the late 19th century with observations on insects and small animals. In 1896, for example, French entomologist Henri Gadeau de Kerville of the Society of Friends of Natural Sciences and the Museum of Rouen published a drawing of two male scarab beetles copulating. Then, during the first half of the 1900s, various investigators described homosexual behavior in baboons, garter snakes and gentoo penguins, among other species. Back then, scientists generally considered homosexual acts among animals to be abnormal. In some cases, they "treated" the animals by, say, castrating them or giving them lobotomies.

At least one early report, however, was more than descriptive, yielding insight into the possible origins of the behavior. In a 1914 laboratory experiment Gilbert Van Tassel Hamilton, a psychopathologist practicing in Montecito, Calif., reported that same-sex behavior in 20 Japanese macaques and two baboons occurred largely as a way of making peace with would-be foes. In the *Journal of Animal Behavior,* Hamilton observed that females offered sex to the more dominant macaques of the same sex: "Homosexual behavior is of relatively frequent occurrence in the female when she is threatened by another female, but it is rarely manifested in response to sexual hunger." And in males, he penned, "homosexual alliances between mature and immature males may possess a defensive value for immature males, since it insures the assistance of an adult defender in the event of an attack."

More recently, some researchers studying bonobos (close relatives of the chimpanzee) have come to similar conclusions. Bonobos seem highly promiscuous by human standards, and about half their sexual activity involves same-sex partners. Female bonobos rub one another's genitals so often that some scientists have suggested that their genitalia evolved to facilitate this activity. The female bonobo's clitoris is "frontally placed, perhaps because selection favored a position maximizing stimulation during the genital-genital rubbing common among females," wrote behavioral ecologist Marlene Zuk, now at the University of Minnesota, in her 2002 book *Sexual Selections: What We Can and Can't Learn about Sex from Animals.* Male bonobos have been observed to mount, fondle and even perform oral sex on one another.



IN THE FRUIT FLY BRAIN, the protein genderblind (*purple*) abuts neurons that communicate using the neurotransmitter glutamate (*green*), a pattern consistent with the idea that genderblind influences a fly's sexual preference by modulating glutamate signaling.

Such behavior seems to ease social tensions. In *Bonobo: The Forgotten Ape* (University of California Press, 1997), Emory University primatologist Frans de Waal and his co-author photographer Frans Lanting noted that "when one female has hit a juvenile and the juvenile's mother has come to its defense, the problem may be resolved by intense [genito-genital] rubbing between the two adults." De Waal has observed hundreds of such incidents, suggesting that they may be a general peacekeeping strategy. "The more homosexuality, the more peaceful the species," asserts Petter Bøckman, an academic adviser at the University of Oslo's Museum of Natural History in Norway. "Bonobos are peaceful."

In fact, such acts are so essential to bonobo socialization that they constitute a rite of passage for young females into

FRANS LANTING *Getty Images* (1); GETTY IMAGES (2); FROM "A GLIAL AMINO-ACID TRANSPORTER CONTROLS SYNAPSE STRENGTH AND COURTSHIP IN *DROSOPHILA*," BY YAEL GROSJEAN ET AL., IN *NATURE NEUROSCIENCE* VOL. 11, NO. 1; JANUARY 2008 (3)

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adulthood. Bonobos live together in groups of about 60 in a matriarchal system. Females leave the group during adolescence and gain admission to another bonobo clan through grooming and sexual encounters with other females. These behaviors promote bonding and give the new recruits benefits such as protection and access to food.

DEFENDED NEST

IN SOME BIRDS, males steal eggs from females and raise them in same-sex unions. This might have evolved as a strategy to increase the survival of the species. "In black swans, if two males find each other and make a nest, they'll be very successful at nest making because they are bigger and stronger than a male and female," Bøckman says. In such cases, he observes, "having a same-sex partner will actually pay off as a sensible life strategy."

In other instances, homosexual bonding between female parents can boost the survival of offspring when male-female pairings are not possible. In birds called oystercatchers, intense competition for male mates would leave some females single were it not for polygamous trios. In a study published in 1998 in *Nature,* zoologist Dik Heg and geneticist Rob van Treuren, both then at the University of Groningen in the Netherlands, observed that roughly 2 percent of oystercatcher breeding groups consist of two females and a male. In some of these families, Heg and van Treuren found, the females tend separate nests and fight over the male, but in others, all three birds watch over a single nest. In the latter case, the females bond by mounting each other as well as the male. The cooperative triangles produce more offspring than the competitive ones because such nests are better tended and protected.

Such arrangements point to the evolutionary fitness of stable social relationships, whatever their type. Biologist Joan E. Roughgarden, now at the University of Hawaii, believes that evolutionary biologists tend to adhere too strongly to Charles Darwin's theory of sexual selection and have thus largely overlooked the importance of bonding and friendship to animal societies and the survival of their young. "[Darwin] equated reproduction with finding a mate rather than paying attention to how the offspring are naturally reared," Roughgarden says.

ZOO POLITICS

Let Them Be Gay

Sometimes zookeepers do not know how to react to their animals' homosexual behavior. In 2005 workers at Bremerhaven's Zoo by the Sea in Germany discovered that three of their five endangered Humboldt penguin couples were of the same sex. The keepers brought in four female Humboldt penguins from Sweden in hopes of tempting the males. That action angered gay and lesbian groups around the world. In a letter to Bremerhaven's then mayor, Jörg Schulz, a group of European gay activists protested what they called "organized and forced harassment through female seductresses."

In the end, the males were not swayed anyway. "The males have scarcely thrown the females a single glance," said zoo director Heike Kück to German magazine *Der Spiegel.* So more males were flown in to keep the Swedish females company. —*E.V.D.*

Protection of progeny, social bonding and conflict avoidance may not be the only reasons animals naturally come to same-sex relationships. Many animals do it simply "because they want to," Bøckman says. "People view animals as robots who behave as their genes say, but animals have feelings, and they react to those feelings." He adds that "as long as they feel the urge [for sex], they'll go for it."

A finding from 2008 indicates that homosexual behavior may be so common because it is rooted in an animal's brain wiring—at least in the case of fruit flies. In a study appearing that year in *Nature Neuroscience,* neuroscientist David E. Featherstone of the University of Illinois at Chicago and his colleagues found that they could switch on homosexual leanings in fruit flies by manipulating a gene for a protein they call "genderblind," which regulates communication between neurons that secrete and respond to the neurotransmitter glutamate.

Males that carried the mutant *genderblind* gene—which depressed levels of the protein by about two thirds—were uncharacteristically attracted to the chemical cues exuded by other males. As a result, these mutant males courted and attempted to copulate with other males. The finding suggests that wild fruit flies may be prewired for both heterosexual and homosexual behavior, the authors write, but that the genderblind protein suppresses the glutamate-based circuits that promote homosexual behavior. Such brain architecture may enable same-sex behavior to surface easily, supporting the notion that it might confer an evolutionary advantage in some circumstances.

THE CAPTIVITY EFFECT

IN SOME LESS SOCIAL SPECIES, homosexual behavior is almost unheard of in wild animals but may surface in captivity. Wild koalas, which are mostly solitary, seem to be strictly heterosexual. But in a 2007 study veterinary scientist Clive J. C. Phillips of the University of Queensland in Brisbane, Australia, and his colleagues observed 43 instances of homosexual activity among female koalas living in a same-sex enclosure at the Lone Pine Koala Sanctuary. The captive females shrieked male mating calls and mated with one another, sometimes participating in multiple encounters of up to five koalas. "The behavior in captivity was certainly enhanced in terms of homosexual activity," Phillips says.

He believes that the females acted this way in part because of stress. Animals often experience stress in enclosed habitats and may engage in homosexual behavior to relieve that tension. A lack of male partners probably also played a role, Phillips suggests. When female koalas are in heat, their ovaries release the sex hormone estrogen, which triggers mating behavior—whether or not males are present. This hardwired urge to copulate, even if expressed with a female partner, might be adaptive. "The homosexual behavior preserves sexual function," Phillips says, enabling an animal to maintain its reproductive fitness and interest in sexual activity. In males, this benefit is even more obvious: homosexual behavior stimulates the continued production of seminal fluid.

A lack of opposite-sex partners is also thought to help explain the prevalence of homosexuality among penguins in zoos. In addition to several gay penguin couplings in the U.S., 20 same-sex penguin

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WILD KOALAS are heterosexual, but females living together in captivity in Brisbane, Australia, shrieked male mating calls and mated with one another.

SILO (*right*) deserted his longtime male partner, Roy (*not shown*) in 2004, in favor of a female chinstrap penguin named Scrappy (*left*).

partnerships were formed in 2004 in zoos in Japan. Such behavior "is very rare in penguins' natural habitats," says animal ecologist Keisuke Ueda of Rikkyo University in Tokyo. Thus, Ueda speculates that the behavior—which included both male pairings and female couplings—arose as a result of the skewed sex ratios at zoos.

Researchers have found still other reasons for homosexual behavior in domesticated cattle—which is such a common occurrence that farmers and animal breeders have developed terms for it. "Bulling" refers to male pairs mounting, and "going boaring" is its female counterpart. For cows, the behavior is not just a stress reliever. It is a way to signal sexual receptivity. The females mount one another to signal their readiness to mate with the bulls—which, in captivity, may cause a breeder to know when to bring in a suitable opposite-sex partner.

Homosexual mounting is much rarer among cattle in the wild, Phillips asserts, based on his research on gaurs in Malaysia, a wild counterpart to domesticated cattle. "Cattle evolved in the forest, so a visual signal was not going to be useful for them," he says.

Stress and the greater availability of same-sex partners may similarly contribute to the practice of homosexual acts among self-described heterosexual humans in environments such as the military, jails and sports teams. In a study published in 2008 in the journal *Sex Roles,* Anderson found that 40 percent of 49 heterosexual former high school football players attending various U.S. universities had had at least one homosexual encounter. These ranged from kissing to oral sex to threesomes that included a woman. In team sports, homosexuality is "no big deal, and it increases cohesion among members of that team," Anderson claims. "It feels good, and [the athletes] bond."

In stressful same-sex environments such as prisons or a war zone, heterosexuals may engage in homosexual behavior in part to relieve tension. "Homosexuality appears mostly in social species," Bøckman says. "It makes flock life easier, and jail flock life is very difficult."

ALTERED SPACES

IN RECENT DECADES zoo officials have tried to minimize the stresses of captivity by making their enclosures more like animals' natural habitats. In the 1950s zoo animals lived behind bars in barren enclosures. But since the late 1970s zoo homes have become more hospitable, including more open space, more objects for animals to play with and better keepers. The Association of Zoos and Aquariums (AZA) regulates everything from cage dimensions to animal bedding. The AZA also outlines enrichment activities for captive creatures: for instance, two golden brown Amur leopards at the Staten Island Zoo regularly play with a papier-mâché zebra, an animal they have never seen in the flesh.

Researchers hope such improvements might affect animal behavior, making it more like what occurs in the wild. One possible sign of more hospitable conditions might be a rate of homosexuality more in line with that of wild members of the same species. Some people, however, contest the notion that zookeepers should prevent or discourage homosexual behavior among the animals they care for [*see box on opposite page*].

And whereas captivity may engender what appears to be an unnaturally high level of homosexual activity in some animal species, human same-sex environments might bring out normal tendencies that other settings tend to suppress. That is, some experts argue that humans, like some other animals, are naturally bisexual. "We should be calling humans bisexual because this idea of exclusive homosexuality is not accurate of people," Roughgarden says. "Homosexuality is mixed in with heterosexuality across cultures and history."

Even Silo the penguin, who had been coupled with Roy for six years, displayed this malleability of sexual orientation. One spring day in 2004 a female chinstrap penguin named Scrappy—a transplant from SeaWorld in San Diego—caught his eye, and he abruptly left Roy for her. Meanwhile Roy and Silo's "daughter," Tango, carried on in the tradition of her fathers. Her chosen mate: a female named Tazuni. SA

Emily V. Driscoll is a science writer and documentary filmmaker in New York.

MORE TO EXPLORE

Biological Exuberance. Bruce Bagemihl. St. Martin's Press, 1999.

Evolution's Rainbow: Diversity, Gender, and Sexuality in Nature and People. Joan Roughgarden. University of California Press, 2004.

A Test of Genetic Models for the Evolutionary Maintenance of Same-Sex Sexual Behaviour. Jessica L. Hoskins, Michael G. Ritchie and Nathan W. Bailey in *Proceedings of the Royal Society B,* Vol. 282, No. 1809; June 22, 2015.

Sexually Antagonistic Selection on Genetic Variation Underlying Both Male and Female Same-Sex Sexual Behavior. David Berger, Tao You, Maravillas R. Minano, Karl Grieshop, Martin I. Lind, Göran Arnqvist and Alexei A. Maklakov in *BMC Evolutionary Biology*, Vol. 16, No. 88; May 13, 2016.

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PAUL McELHONE Getty Images (koalas); CHANG W. LEE New York Times/Redux Pictures (penguins)

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SELECTION FROM THE SCIENTIFIC AMERICAN BOOK IMPRINT

Scientists have figured out how venom injected by a tiny wasp turns a cockroach into its puppet—and into the perfect live meal for its offspring

By Christie Wilcox

ZOMBIE NEUROSCIENCE

I DON'T KNOW IF COCKROACHES DREAM, BUT I IMAGINE THAT IF THEY DO, JEWEL WASPS feature prominently in their nightmares. These small, solitary tropical wasps are of little concern to us humans; after all, they don't manipulate our minds so that they can serve us up as willing, living meals to their newborns, as they do to unsuspecting cockroaches. It's the stuff of horror movies, quite literally: the jewel wasp and similar species inspired the chest-bursting horrors in the *Alien* franchise. The story is simple, if grotesque: the female wasp controls the minds of the cockroaches she feeds to her offspring, taking away their sense of fear or will to escape their fate. But unlike what we see on the big screen, it's not some incurable virus that turns a once healthy cockroach into a mindless zombie—it's venom. Not just any venom, either: a specific venom that acts like a drug, targeting the cockroach's brain.

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Brains, at their core, are just neurons, whether we're talking human brains or insect brains. There are potentially millions of venom compounds that can turn neurons on or off. So it should come as no surprise that some venoms target the carefully protected *central* nervous system, including our brains. Some leap their way over physiological hurdles, from remote injection locations around the body

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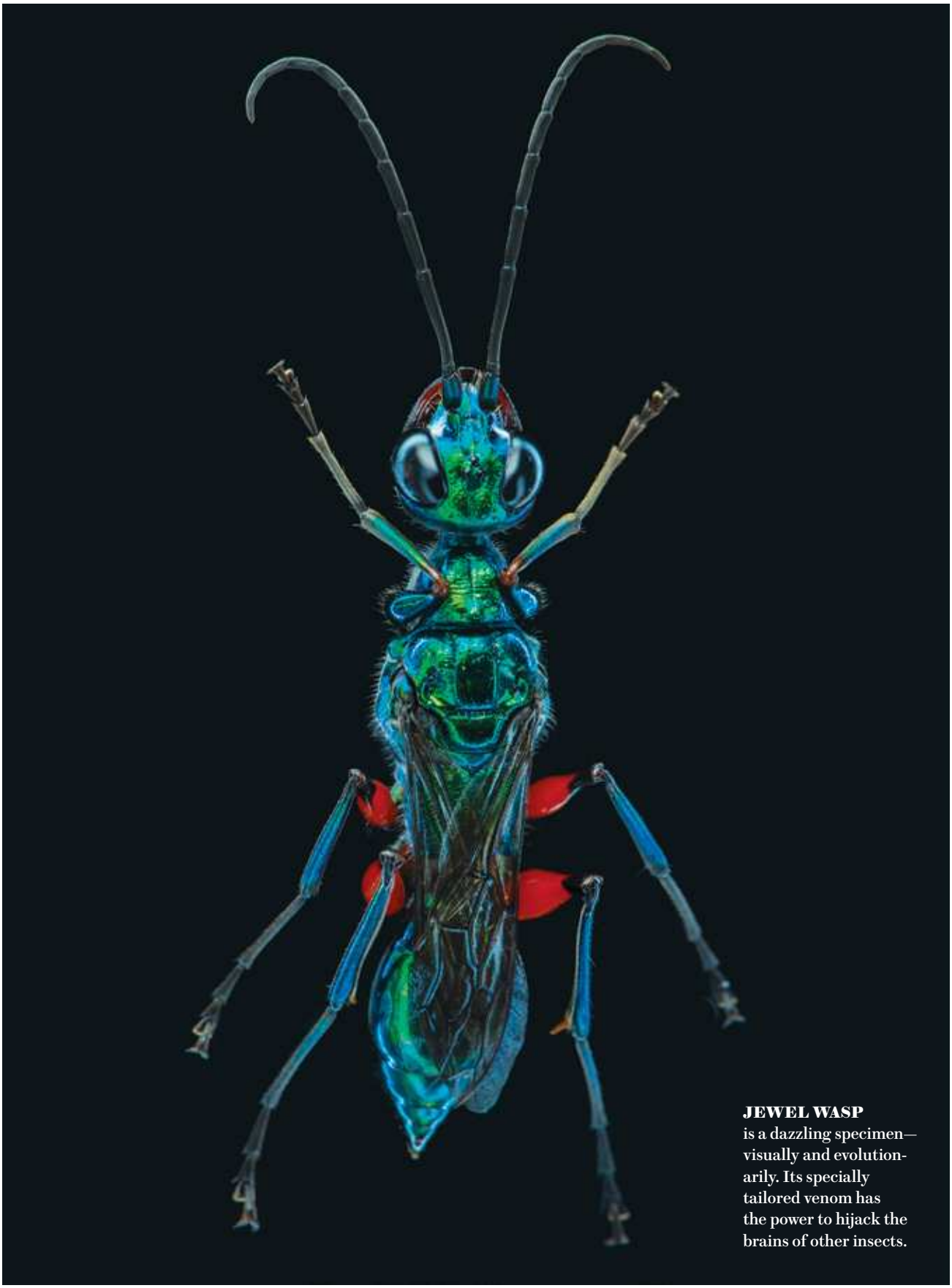

JEWEL WASP is a dazzling specimen—visually and evolutionarily. Its specially tailored venom has the power to hijack the brains of other insects.

ANAND VARMA *National Geographic Creative*

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and past the blood-brain barrier, to enter their victims' minds. Others are directly injected into the brain, as in the case of the jewel wasp and its zombie cockroach host.

MAKING OF A ZOMBIE

JEWEL WASPS are a beautiful if terrifying example of how neurotoxic venoms can do much more than paralyze. The wasp, which is often just a fraction of the size of her victim, begins her attack from above, swooping down and grabbing the roach with her mouth as she aims her "stinger"—a modified egg-laying body part called an ovipositor—at the middle of the body, the thorax, in between the first pair of legs. The quick jab takes only a few seconds, and venom compounds work fast, paralyzing the cockroach temporarily so the wasp can aim her next sting with more accuracy. With her long stinger, she targets her mind-altering venom into two areas of the ganglia, the insect equivalent of a brain.

The wasp's stinger is so well tuned to its victim that it can sense where it is inside the cockroach's dome to inject venom directly into subsections of its brain. The stinger is capable of feeling around in the roach's head, relying on mechanical and chemical cues to find its way past the ganglionic sheath (the insect's version of a blood-brain barrier) and inject venom exactly where it needs to go. The two areas of the roach brain that she targets are very important to her; scientists have artificially clipped them from cockroaches to see how the wasp reacts, and when they are removed, the wasp tries to find them, taking a long time with her stinger embedded in search of the missing brain regions.

Then the mind control begins. First the victim grooms itself, of all things; as soon as the roach's front legs recover from the transient paralysis induced by the sting to the body, it begins a fastidious grooming routine that takes about half an hour. Scientists have shown that this behavior is specific to the venom, as piercing the head, generally stressing the cockroach, or contact with the wasp without stinging activity did not elicit the same hygienic urge. This sudden need for cleanliness can also be induced by a flood of dopamine in the cockroach's brain, so we think that the dopaminelike compound in the venom may be the cause of this germophobic behavior. Whether the grooming itself is a beneficial feature of the venom or a side effect is debated. Some believe that the behavior ensures a clean, fungus- and microbe-free meal for the vulnerable baby wasp; others think it may merely distract the cockroach for some time as the wasp prepares the cockroach's tomb.

Dopamine is one of those intriguing chemicals found in the brains of a broad spectrum of animal life, from insects all the way to humans, and its effects are vital in all these species. In *our* heads, it's part of a mental "reward system": floods of dopamine are triggered by pleasurable things. Because it makes us feel good, dopamine can be wonderful, but it is also linked to addictive behaviors and the "highs" we feel from illicit substances like cocaine. It's impossible for us to know if a cockroach also feels a rush of insect euphoria when its brain floods with dopamine—but I prefer to think it does. (It just seems too gruesome for the animal to receive no joy from the terrible end it is about to meet.)

HAVING GROWN—and nourished itself—inside its cockroach host, a wasp offspring emerges to start the macabre life cycle anew.

While the cockroach cleans, the wasp leaves her victim in search of a suitable location. She needs a dark burrow where she can leave her child and the zombie-roach offering, and it takes a little time to find and prepare the right place. When she returns about 30 minutes later, the venom's effects have taken over—the cockroach has lost all will to flee. In principle, this state is temporary: if you separate an envenomated roach from its would-be assassin before the larva can hatch and feed and pupate, the .zombification wears off within a week. Unfortunately for the envenomated cockroach, that's simply too long. Before its brain has a chance to return to normal, the young wasp has already had its fill and killed its host.

The motor abilities of the roach remain intact, but the insect simply doesn't seem inclined to use them. So the venom doesn't numb the animal's senses—it alters how its brain responds to them. Scientists have even shown that the stimuli that normally elicit evasive action, such as touching the roach's wings or legs, still send signals to the animal's brain; they just don't evoke a behavioral response. That's because the venom mutes certain neurons so they are less active and responsive, leading to the roach's sudden lack of fear and willingness to be buried and eaten alive. This venom activity requires toxins that target GABA-gated chloride channels.

GABA, or γ-aminobutyric acid, is one of the most important neurotransmitters in insect—and human—brains. If neuron activity is a party, then GABA is a wet blanket; it dampens a neuron's ability to be triggered through activation of chloride channels. When chloride channels open, they allow negative chloride ions to flow. Because these ions like to hang out with

IN BRIEF

The jewel wasp depends on live cockroaches to provide crucial food for its newly hatched larvae.

To force cockroaches into submission and into a necessary torpor, the wasp has evolved a particular chemical mix that it injects into a roach's brain to alter its behavior and metabolism.

Many other wasp species also use complex venoms to parasitize spiders, caterpillars and even wasp larvae—sometimes turning them into zombie larva defenders.

ALAMY

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positive ions, if these channels are open when a sodium channel happens to open, chloride ions can cross the membrane at almost the same pace as sodium ions, making it harder for the sodium ions to start the domino cascade that is neuron signaling. Even though a neuron receives the "go" command, the action potential is stopped in its tracks. GABA isn't a complete inhibitor, however—the chloride channels can't wholly keep up with the sodium channels, so a strong stimulus can overcome the dampening effect. This dulling system is what the wasp co-opts to make the cockroach do her bidding. Her venom is packed with GABA and two other compounds that also activate the same chloride receptors, β-alanine and taurine. These also work to prevent the reuptake of GABA by neurons, prolonging the effect.

Although these venom compounds can cut the brain activity that would make her prey flee, what they can't do is make their way to the right parts of the cockroach brain by themselves. That's why the wasp has to inject them directly into the cockroach's ganglia. Fortunately for her, in a convenient quirk of nature, the same venom that zombifies roach brains works like magic to produce the transient paralysis needed to line up the cranial injection. GABA, β-alanine and taurine also temporarily shut down motor neurons, so the wasp needs only one venom to complete two very different tasks.

With her prey calm and quiescent, the wasp can replenish her energy by breaking the roach's antennae and drinking some sweet, nutritious insect blood. Then she leads her victim to its final resting place, using what remains of an antenna as an equestrian uses the reins on a bridle. Once inside her burrow, she attaches one egg to the cockroach's leg, then seals her offspring and the roach in.

ONCE INSIDE HER BURROW, THE WASP ATTACHES ONE EGG TO THE COCKROACH'S LEG, THEN SEALS HER OFFSPRING AND THE ROACH IN.

FRESH MEALS

AS IF THE MIND MANIPULATION wasn't bad enough, the wasp's venom has one final trick. While the roach awaits its inevitable doom, the venom slows down the roach's metabolism to ensure it lives long enough to be devoured still fresh. One way metabolism can be measured is by how much oxygen is used up over time, as all animals (including us) use oxygen in the process of creating energy from food or fat stores. Scientists have found that oxygen consumption by cockroaches that have been stung is much lower than that of their healthy roach friends. They thought this might be the result of the reduced movement of the complacent victims, but even when paralysis is induced by using drugs or severing neurons, the stung cockroaches live longer. The key to the prolonged survival seems to be hydration. How exactly the venom acts to keep a roach hydrated is not known, but it ensures that when the wasp larva hatches from its egg, its meal is ready to eat. And soon enough after that, a new wasp emerges from the burrow, leaving the roach carcass behind.

Jewel wasp venom is only one example of neurotoxic venom taken to the extreme. There are more than 130 species in the same wasp genus, including the newly described *Ampulex dementor* (named for the soul-sucking guards of the magical prison Azkaban in the *Harry Potter* series). *Ampulex* belongs to a very large and diverse group of wasps, numbering at least in the hundreds of thousands of species, which are known for some serious mental manipulation. All have a macabre life cycle: as adults, they feed like other wasps and bees, but as larvae, they must feed off other animals. They're not quite independent, not quite parasites—they're parasite-ish, or as scientists call them, parasitoids.

Cockroaches are not their only targets; there are parasitoid wasps that lay their eggs in spiders, caterpillars and ants. The temperate Northern Hemisphere wasp *Agriotypus* will dive underwater to attach her eggs to caddis fly larvae and can remain submerged for up to 15 minutes to accomplish her task. The brave *Lasiochalcidia* wasps of Europe and Africa throw themselves into the nightmarish jaws of an ant lion, pry them apart and insert their eggs into its throat. There are even wasps called hyperparasitoids that parasitize other wasps like themselves, such as *Lysibia* species of Europe and Asia, which will sniff out caterpillars parasitized by fellow parasitoid wasps in the genus *Cotesia* and lay eggs in the freshly pupated wasp larvae. In some cases, multiple wasp species parasitize one another, leading to a Russian doll of parasitic interactions.

And to ensure their safe passage from larva to adulthood, these wasps often gain more than just a meal from their hosts. One of them turns its caterpillar hosts into undead bodyguards that will defend pupating young wasps that just ate through its body. Another species' larva forces its spider host to spin it a deformed but durable web to protect its cocoon just before killing the arachnid.

Whereas the wasps in this unusual family may have perfected the art of mind control, there are other venomous species whose toxins alter mental states. There are even species whose neurotoxic compounds get through our own blood-brain barrier, a feat that no wasp venom can yet achieve. But unlike cockroaches, we *Homo sapiens* have a strange affinity for substances that mess with our minds. Although the roaches run from those that would twist their brains, some people are willing to pay upward of $500 for a dose of venom to have a similar experience. SA

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MORE TO EXPLORE

A Wasp Manipulates Neuronal Activity in the Sub-Esophageal Ganglion to Decrease the Drive for Walking in Its Cockroach Prey. Ram Gal and Frederic Libersat in *PLOS ONE*, Vol. 5, No. 4, Article No. e10019; April 7, 2010.

The Soul-Sucking Wasp by Popular Acclaim—Museum Visitor Participation in Biodiversity Discovery and Taxonomy. Michael Ohl et al. in *PLOS ONE*, Vol. 9, No. 4, Article No. e95068; April 22, 2014.

The Role of the Cerebral Ganglia in the Venom-Induced Behavioral Manipulation of Cockroaches Stung by the Parasitoid Jewel Wasp. Maayan Kaiser and Frederic Libersat in *Journal of Experimental Biology*, Vol. 218, No. 7, pages 1022–1027; April 1, 2015.

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The Social Genius of Animals

Research shows that animals interact in amazingly sophisticated ways

By Katherine Harmon Courage

IN BRIEF

Only recently have researchers realized the extent of animals' social intelligence—their ability to understand and learn from others.

Animals may teach one another important skills, such as how to use tools.

Some critters can deceive. Intuiting what others know enables an animal to trick another member of the same species for personal gain.

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AT THE THAI ELEPHANT CONSERVATION CENTER, TUCKED AWAY IN THE trees near Chiang Mai, a pair of Asian elephants gazes at two bowls of corn on the other side of a net. The corn is attached to a sliding platform, through which researchers have threaded a rope. The rope's ends lie on the elephants' side of the net. If only one elephant pulls an end, the rope slides out of the contraption. To bring the food within trunk's reach, the elephants have to do something only humans and other primates were until recently thought to do: they must cooperate. Working in synchrony, each elephant grabs its end of the rope in its trunk and pulls, drawing the platform and the treats within reach.

Six pairs of these large animals succeeded in solving this double rope puzzle. A lone elephant would wait as long as 45 seconds for a partner to arrive, showing it knew it needed a buddy to get the job done. Psychologist Joshua M. Plotnik, now at Hunter College, the City University of New York, and his colleagues, who documented these findings in 2011, also noticed that the elephant duos used different strategies for obtaining the food, suggesting that the animals had developed a deep understanding of social cooperation.

In the past century animals have repeatedly surpassed our expectations for their intellect. Koko the gorilla learned sign language; Alex the African grey parrot boasted a spoken vocabulary of more than 150 words; and even invertebrates such as the octopus have been seen using tools in the wild. Until the mid-20th century, we assumed only humans could use tools and learn meaningful pieces of a language. Sophisticated social skills such as cooperation were presumed to be way beyond animals' cognitive reach. Only now have researchers begun to realize the extent of animals' social intelligence, their ability to understand and learn from others.

Recent findings suggest that some animals are not only capable of creating social connections but that many use them for survival. As with people, some animals have social needs. They notice when another member of their species is distracted, and they are able to figure out an effective way to get its attention. Animals may teach one another important skills, such as how to use tools. Some critters can even deceive. Intuiting what others know enables them to trick one of their kind for personal gain. The animals described below have some of the most impressive social abilities in the animal kingdom. Studying how they interact is giving scientists new insight into what they know—and a glimpse at what might be the upper limits of animal intelligence.

MAKING CONNECTIONS

IN OUR OWN LIVES, social intelligence might seem to play second fiddle to, say, the ability to do calculus or write a book. Individuals held up as modern geniuses, however, such as Stephen Hawking or the late Steve Jobs, have not only exceptional analytic skills but also an extraordinary ability to relate their ideas to a broader audience. These social skills are fundamental to our complex society. Without the ability to form a cohesive group, communicate ideas or collectively solve problems, humans could not have built the great pyramids or the first supercomputers.

DOGS SEEM TO NOTICE WHETHER A DOG THEY WANT TO PLAY WITH IS READY TO RECEIVE THEIR PLAY SIGNAL. THEY SEEM TO REACT TO DISTINCT COGNITIVE STATES OF OTHER DOGS.

Social skills require, first, a basic affinity for others. "You can't evolve all of the computational systems for social intelligence until you have that tendency that you want to be close to others," says biologist Louis Lefebvre of McGill University. Not all animals have this. Octopuses, for example, seek one another out only to procreate.

In contrast, zebra finches form monogamous pairs and congregate in groups. In a 2009 study the late biologist James Goodson of Indiana University Bloomington and his colleagues drilled down to the chemical essence of this social instinct: mesotocin, the bird equivalent of the human hormone oxytocin, which is implicated in bonding. When the researchers blocked mesotocin in the brains of the birds, they shrugged off their fellow finches. Females spent less than one third as much time near their same-sex cage mates after the treatment than before it. Extra doses of mesotocin had the opposite effect: the birds became even more social than they typically are.

Goodson and his colleagues also examined the biology of this hormone in other species of finches with different degrees of social affinity. The team found fewer receptors for mesotocin in key spots of the brain in species that were more territorial (less social) than the ze-

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bra finch—and more receptors in species that traveled in flocks. Scientists have identified similar patterns of brain chemicals and social preferences in many mammals. In prairie voles, for example, how mates bond with one another and their children is also associated with different levels of oxytocin and vasopressin, another hormone linked to social behavior and bonding.

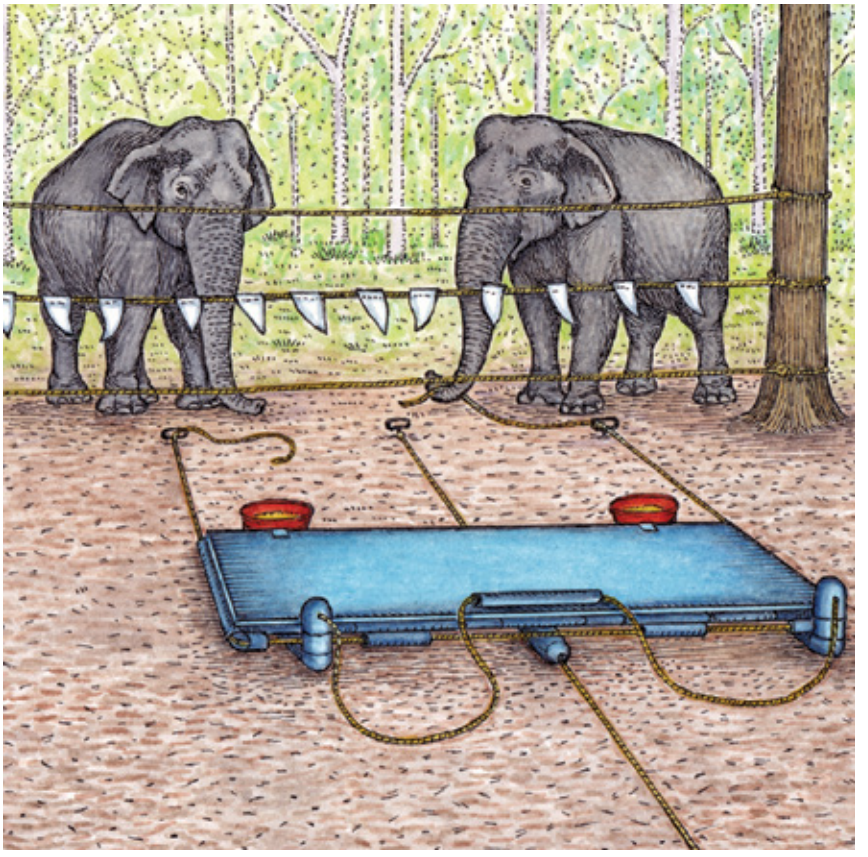
KNOW YOURSELF—AND OTHERS

GOOD SOCIAL GRACES also require a sense of the self as distinct from others. This primitive level of self-awareness allows animals to go beyond acting out a programmed set of behaviors for mating or for defense.

Researchers test self-awareness by placing a visible mark on an animal and showing it a mirror. An animal passes the test if it appears to recognize that the dot is on its body as opposed to on the "other" animal in the mirror. It can signal this awareness, for example, by reaching toward the spot on its own body. Great apes, elephants, bottlenose dolphins, orcas and magpies have all passed, suggesting they have more social prowess than animals that simply flock or school together.

The second requirement for social networking is an understanding that others have different mental states—knowledge, desires, beliefs or intents—and that at any given moment another individual might be in a mental state that is different from the one you are in. This ability is called theory of mind. Psychologists often test its development in young children by having a child and an adult observe a researcher place an object in a specific location, say, a ball in a cup. The adult leaves the room, and the ball is moved. After the adult returns, a child with a mature theory of mind understands that the adult does not know the ball has moved, and he or she does not expect the adult to look for it in the new location. Similar theory-of-mind tests are difficult to conduct in animals because it is hard to communicate with them directly.

Nevertheless, we can glean hints from their physiology, such as the presence of so-called mirror neurons. These cells, which have been found in macaques and birds, swing into action when an animal sees another individual doing something. In humans, they are thought to exist in various brain regions, including the supplementary motor area, a small patch of tissue at the top of the head that helps to control movement. Because these cells' activity patterns mirror the behavior of others and to some extent reflect the movement's goal, they may enable animals to understand others' actions, possibly even their intentions. They might underlie the ability to learn motor actions by observation and also buttress a theory of mind.



ELEPHANT PAIR can slide bowls of corn within reach if they work together, each pulling one end of a rope. Dogs have been shown to cooperate similarly.

Mirror neurons have not yet been discovered in dogs, but more than a decade ago psychologist Alexandra Horowitz of Barnard College collected behavioral data suggesting that dogs may have some version of a theory of mind. Over the course of 21 months Horowitz videotaped a random sampling of dogs at play in a San Diego dog park. When she analyzed the footage, she noticed some interesting behaviors that suggested dogs could be aware of another dog's perspective.

The dogs at the park varied how they signaled a desire to play depending on the other dog's position. If a prospective playmate was already facing it, the dog gave a visual signal—opening its mouth wide or bowing down into that familiar bottom-up play pose. But if the other dog was turned away and otherwise engaged, it might instead give its friend a little nip. "They seem to be noticing whether a dog they wanted to play with was ready to receive their play signal," Horowitz says. "They seem to be reacting to distinct cognitive states" of others. Based on her research Horowitz has posited that dogs possess at least a rudimentary theory of mind.

Consistent with the mirror neuron findings, many monkeys and some birds have demonstrated in their behavior at least some capacity for theory of mind. Monkeys, birds and dogs are exceptions, however. In most animal species, scientists have failed to see even a glimmer of evidence for this advanced social capacity.

SCHOOLS AND STUDENTS

AMONG ITS MANY BENEFITS, social intelligence confers the ability to distribute information. Scientists have long ob-

Illustrations by Patricia J. Wynne

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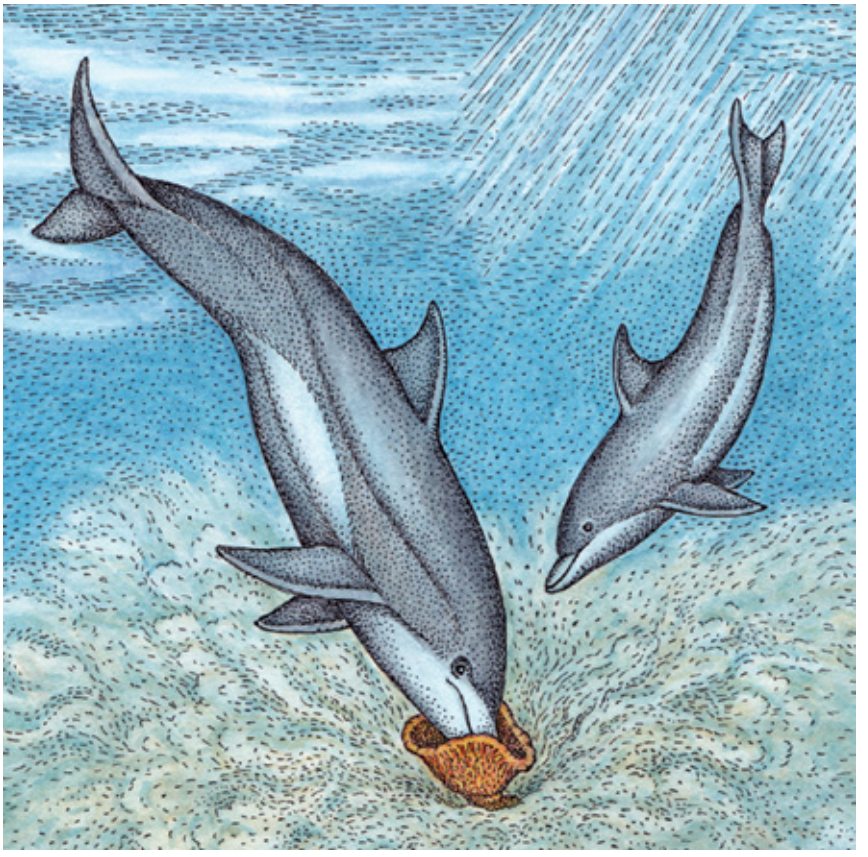
served that herd animals can give warning signals if a predator is approaching; for example, a white-tailed deer may flash its conspicuous white tail, pointing it upward before bolting. Now, however, researchers are noticing that some animals that live in groups can teach one another rules of social engagement or ways to create a tool.

Zebra fish, for example, seem to transmit subtle social cues to other members of their school. These small creatures can make an easy meal for larger fish in the wild, so they tend to be cautious of new objects. If they are reared in captivity, however, they show little fear of a moving object, swimming within close proximity of it.

A team of researchers led by biologist Sarah Zala of the Konrad Lorenz Institute of Ethology at the University of Veterinary Medicine in Vienna wanted to know if these fish would change their behavior if surrounded by others that acted differently. The group introduced some shy, wild zebra fish to more brazen domestic ones. The wild ones learned from their new acquaintances to be bolder when a moving object was introduced near the tank. Instead of swimming away from it, they joined their fearless new companions and ventured toward it. When the emboldened wild fish were separated from their new friends, they still bravely swam near novel things. The results indicate these fish had not just mindlessly followed the other fish but had learned a new behavior.

Dolphins can convey more intricate behaviors to others. One group of bottlenose dolphins in Australia uses a technique called sponging to find food. Biologist Janet Mann of Georgetown University and her colleagues saw the females sporting a sea sponge on their snout, a technique that seemed to allow the dolphins to push along the seafloor to look for fish and other food without hurting their nose. The scientists sampled DNA from these sponging mammals and compared it with DNA from area dolphins that did not use this tactic. They discovered that the sponging dolphins, but not the others, had a common maternal line. In a report of the findings, the researchers suggested that mothers in this particular group managed to teach this complex act to their daughters.

Mother chimpanzees also use social learning to hand down wisdom to daughters. Young female chimps at the Gombe National Park in Tanzania are much handier at making tools to retrieve termites than are males. Adult females there use long twigs or stems to fish out termites, whereas males are more likely to kill larger game for their meals. In a study published in 2004, Elizabeth Lonsdorf of the Lincoln Park Zoo in Chicago and her colleagues found that the younger females spent more time with their mothers learning this skill than did the males, who were more likely to be playing—perfecting their social skills for later battles for dominance, mates and food.



ONE STUDY SUGGESTS that certain dolphin mothers teach their daughters to don a sea sponge on their snout to guard against injuries while they scour the seafloor for fish.

DECEPTION

SOCIAL LEARNING can be a big advantage for a group or species, which can transmit the most successful strategies to others. Some animals, however, use their social awareness for personal gain by hiding information from potential competitors. A group led by psychologist Federica Amici, then at Liverpool John Moores University in England, trained low-ranking capuchin monkeys, long-tailed macaques and spider monkeys to unlock a box to obtain a food reward. When alone, these monkeys unlocked the box and indulged. But when a dominant monkey was around, the trained animals—especially the macaques—chose to forgo the hidden treat, ignoring the box so as not to reveal how to open it.

Some species of birds engage in a similar type of deceit, bolstering the argument that these animals might also possess some theory of mind. Whether in a laboratory or the wild, Western scrub jays are more likely to move their food stashes when other birds are around. In fact, lab experiments have shown that scrub jays will either move or pretend to move a newly caught worm if they think another bird might have seen them bury it. This behavior suggests some awareness of what the other individual knows and how they can protect their own interests. "Nonprimate species are thinking about these things in some very clev-

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WHEN A SCRUB JAY spots another bird eyeing its food stash, it will move or pretend to move its edibles, indicating that these birds are cognizant of what their fellow jays know.

er ways," says psychologist Laurie Santos of Yale University.

At least one of the cooperating Asian elephants in Plotnik's experiments also learned how to game the social system. The elephant, named Neua Un, figured out that instead of pulling on her side of the rope, she could stand on her end so it would not slip. Then she let the other elephant do all of the hard work. She also moved her trunk every now and then, as if to convince her partner that she, too, was pulling.

EMOTIONAL APTITUDE

OF COURSE, SOCIAL IQ involves more than knowing how to get another person's attention or teaching the young new information and skills. A deeper social intelligence, one that allows for empathy and grief, is arguably the intangible, almost indescribable fiber that weaves us together. It is tied to our emotional well-being, and as new studies about longevity are showing, these rich social connections are important to our physical health as well. Although we might not be able to ask animals directly how they think and feel about others, we can watch them for clues.

In a 2010 paper psychologist James Anderson, then at the University of Stirling in Scotland, and his colleagues described video footage of an adult female chimp named Rosie and her companions, which lived at the nearby Blair Drummond Safari and Adventure Park, reacting to the death of her elderly mother. Rosie did not eat as much, sleep as soundly or show as much energy as usual for weeks after her mother died, suggesting that the animal may have been in mourning. Other apes, including gorillas in the Democratic Republic of the Congo's Virunga National Park, displayed similar patterns after the death of a parent or a peer.

Behaviors that suggest grief over the death of a relative or close companion have also been observed in dogs, cats and other species ranging from dolphins to ducks [see "When Animals Mourn," by Barbara J. King, on page 64]. It is difficult, however, to determine whether a specific behavior—such as waiting for a companion's return—is an expression of grief or even to what extent various animals can comprehend death.

Grief is not the only complex emotion that animals may feel. Psychologist Frans de Waal of Emory University and his colleagues have demonstrated that chimpanzees prefer actions that will help peers to those that just benefit themselves, indicating that they are inclined toward altruism—a highly social quality once thought to be the exclusive domain of humans.

Social intelligence, as distinctive and intricate as it is, may not be easily separable from other forms of smarts such as problem-solving ability or knowledge of the world. For example, a scrub jay that moves its food stores to keep them secret has performed both social and nonsocial mental gymnastics, including, Lefebvre says, "sophisticated memory mechanisms and time travel [that project] future needs for food." Yet although brilliance very likely has multiple facets, social cunning is one important—and often underappreciated—element. Indeed, the smarter we humans become about assessing the social intelligence of animals, the more closely related to us they may seem. SA

Katherine Harmon Courage is a freelance journalist. Her first book, *Octopus! The Most Mysterious Creature in the Sea* (Current/Penguin, 2013), examines that animal's famed intelligence. Her forthcoming book *Cultured* explores the microbiome and food.

MORE TO EXPLORE

Elephants Know When They Need a Helping Trunk in a Cooperative Task. Joshua M. Plotnik et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 108, No. 12, pages 5116–5121; March 22, 2011.

Monkeys Represent Others' Knowledge but Not Their Beliefs. Drew C. W. Marticorena et al. in *Developmental Science,* Vol. 14, No. 6, pages 1406–1416; November 2011.

Theory of Mind in Dogs? Examining Method and Concept. Alexandra Horowitz in *Learning and Behavior,* Vol. 39, No. 4, pages 314–317; December 2011.

Social Cognition. Robert M. Seyfarth and Dorothy L. Cheney in *Animal Behavior,* Vol. 103, pages 191–202; May 2015.

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SELECTION FROM THE SCIENTIFIC AMERICAN BOOK IMPRINT

Some fish species turn out to be very good problem solvers. At times, they even use tools

By Jonathan Balcombe

EINSTEIN OF THE SEA

WHILE DIVING OFF THE MICRONESIAN ARCHIPELAGO OF PULAU, EVOLUTIONARY biologist Giacomo Bernardi witnessed something unusual and was lucky enough to capture it on film. An orange-dotted tuskfish (*Choerodon anchorago*) uncovered a clam buried in the sand by blowing water at it, picked up the mollusk in its mouth and carried it to a large rock 30 yards away. Then, using several rapid head flicks and well-timed releases, the fish eventually cracked open the clam against the rock. In the ensuing 20 minutes, the tuskfish ate three clams, using the same sequence of behaviors to smash them.

Bernardi, a professor at the University of California, Santa Cruz, is thought to be the first scientist to film a fish demonstrating tool use. By any measure, it is remarkable behavior from a fish. Tool use was long believed unique to humans, and it is only in the past decade that scientists have begun to appreciate the behavior beyond mammals and birds.

Bernardi's video unveils new gems every time I watch it. Initially I failed to notice that the enterprising tuskfish does not uncover the clam in a manner we might expect—by blowing jets of water from its mouth. The fish actually turns away from the target and snaps its gill cover shut, generating a pulse of water the same way that a book creates a puff of air when you close it. And it is more than tool use. By using a logical series of flexible behaviors separated in time and space, the tuskfish is a planner. This behav-

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ARCHERFISH squirts precisely tuned jets of water to knock down unsuspecting prey.

WARREN PHOTOGRAPHIC

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ior brings to mind chimpanzees' use of twigs or grass stems to draw termites from their nests. Or Brazilian capuchin monkeys that use heavy stones to smash hard nuts against flat boulders that serve as anvils. Or crows that drop nuts onto busy traffic intersections and then swoop down during a red light to retrieve the fragments that the car wheels have cracked open for them.

Halfway to its destination, our tuskfish stops to try out a smaller rock lying on the sand. It makes a couple of halfhearted whacks, then heads on its way again, as if it has decided this one is not worth his time. (Who can't relate to these misguided attempts and how they reflect the fallibility of a mortal life?)

These are impressive cognitive feats for any animal. That they are performed by a fish clearly upsets the still commonly held assumption that fishes are at the dim end of the animal intelligence spectrum. As does the realization that what Bernardi saw that day was not exceptional. Scientists have noticed similar behavior in green wrasses, also called blackspot tuskfish (*Choerodon schoenleinii*), on Australia's Great Barrier Reef; in yellowhead wrasses (*Halichoeres garnoti*) off the coast of Florida; and in a sixbar wrasse (*Thalassoma hardwicke*) in an aquarium setting. In the case of the sixbar wrasse, the captive fish was given pellets that were too large to swallow and too hard to break into pieces using only its jaws. The fish carried one of the pellets to a rock in the aquarium tank and smashed it much as the tuskfish did the clam. The zoologist who observed this, Łukasz Paśko of the University of Wrocław in Poland, saw the wrasse perform the pellet-smashing behavior on 15 occasions, and it was only following many weeks of captivity that he had first noticed it. Paśko described the behavior as "remarkably consistent" and "nearly always successful."

Hard-nosed skeptics might point out that this kind of thing is not *real* tool use because the fishes are not wielding one object to manipulate another, as humans do with an ax splitting a log for firewood or chimpanzees do by using a stick to get to the tastiest termites. Paśko himself refers to the wrasse's actions as "tool-like." But this is not to demean the behavior, because, as he points out, smashing a clam or a pellet with a separate tool is simply not an option for a fish. For one thing, a fish is not equipped with grasping limbs. In addition, the viscosity and density of water make it difficult to generate sufficient momentum with an isolated tool (try smashing a walnut shell underwater by throwing it against a rock). And clasping a tool by mouth, the fish's other practical option, is inefficient because fragments of food would float away, only to be snatched up by other hungry swimmers.

EXPERT AIM

JUST AS THE TUSKFISH uses water as a force for moving sand, the archerfish (*Toxotes*) also uses water as a force—only this time as a hunting projectile. These four-inch-long tropical marksmen—sporting a row of handsome black patches down their silvery sides—mostly inhabit brackish waters of estuaries, mangroves and streams from India to the Philippines, Australia and Polynesia. Their eyes are sufficiently wide, large and mobile to allow binocular vision. They also have an impressive underbite, which they use to create a gun barrel of sorts. By pressing their tongue against a groove in the upper jaw and suddenly compressing the throat and mouth, archerfish can squirt a sharp jet of water up to 10 feet through the air—with an accuracy in some individuals of nearly 100 percent at a distance of three feet. Woe betide a beetle or a grasshopper perched on a leaf above the backwaters where these fish lurk.

The behavior is notably flexible. An archerfish can squirt water in a single shot or in a machine gun–like fusillade. Targets have included insects, spiders, an infant lizard, bits of raw meat, scientific models of typical prey and even observers' eyes—along with their lit cigarettes. Archerfish also load their weapons according to the size of their prey, using more water for larger, heavier targets. Experienced archers may even aim just below their prey on a vertical surface to knock it straight down into the water instead of farther away on land.

Using water as a projectile is only one of many foraging options for the archerfish. Most of the time this species forages underwater as ordinary fishes do. And if a meal is within just a foot of the surface of the water, they may just take the more direct route, leaping to snatch it in their mouth.

Archerfish live in groups, and they have fantastic observational learning skill. Their hunting prowess does not come preinstalled, so novices can make successful shots at speedy targets only after a prolonged training period. Researchers studying captive archerfish at the Friedrich-Alexander University of Erlangen-Nuremberg in Germany found that inexperienced individuals were not able to successfully hit a target even if it was moving as slowly as half an inch per second. But after watching 1,000 attempts (successful and unsuccessful) by another archerfish to hit a moving target, the novices were able to make successful shots at rapidly moving targets. The scientists concluded that archerfish can assume the viewpoint of another archerfish to learn a difficult skill from a distance. Biologists call this "perspective taking." What an archerfish does might not require the same level of cognition as that shown by a captive chimp that has carried a disabled starling up a tree to help launch it back to the air, but it is nonetheless a form of grasping something from the perspective of another.

High-speed video recordings reveal that these fish use different shooting strategies depending on the speed and location of flying prey. When using what the researchers describe as the "predictive leading strategy," archerfish adjust the trajectory of their jets of water to account for the speed of a flying insect—they aim farther ahead of the target if it is moving faster. If the target is flying low (usually less than seven inches above the water), archerfish often use a different strategy, which the researchers term "turn and shoot." This maneuver involves the fish firing

IN BRIEF

Fishes have long been dismissed as dullards, but new observations and studies are proving this assumption wrong.

One species of wrasse, for instance, has been filmed engaging in a marine version of tool use.

Archerfish, which capture prey with precisely calibrated jets of water, are showing how fishes can learn complex skills—and that they can mentally place themselves in the position of a fellow fish.

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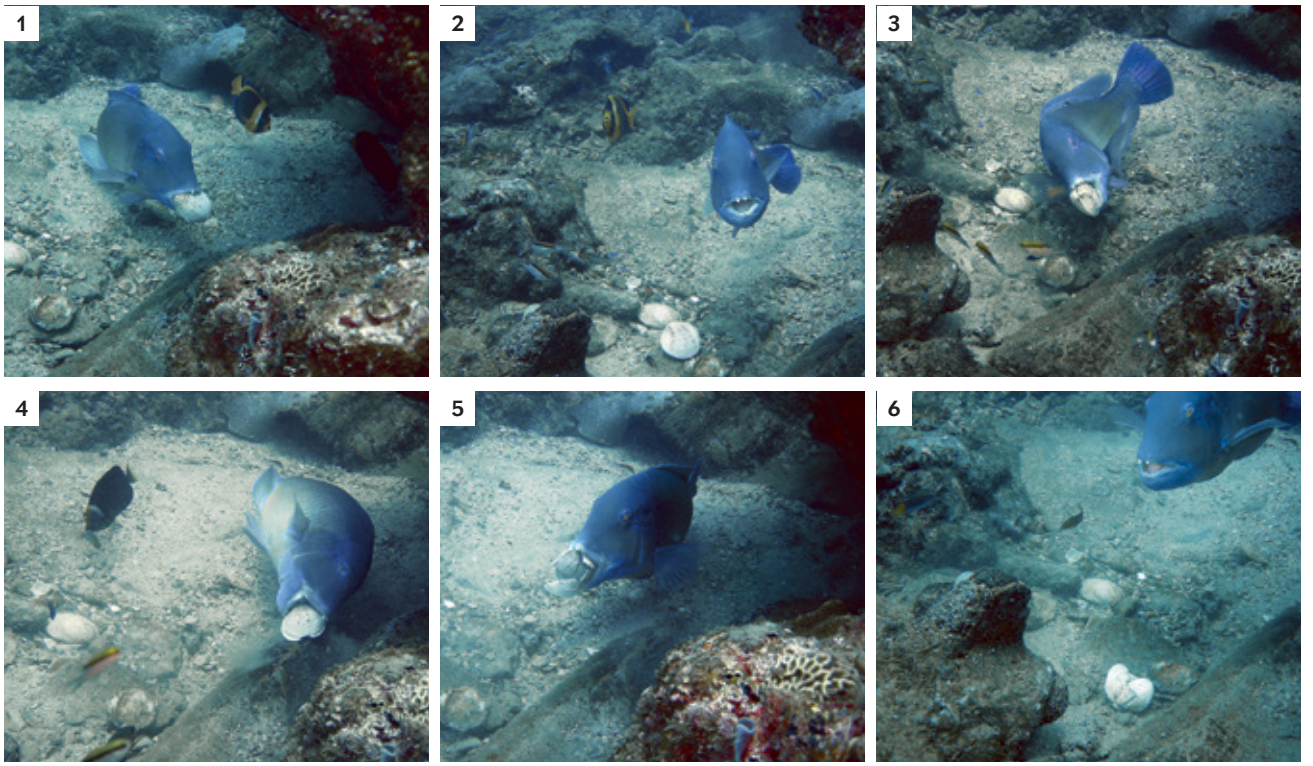

BLACKSPOT TUSKFISH opens a cockle by smashing it onto a rock, which some scientists suggest is an example of tool use.

COURTESY OF SCOTT GARDNER

while simultaneously rotating its body horizontally to match the lateral movement of the target, causing the jet of water to "track" the target on its airborne path. These fish would do any quarterback proud.

Archerfish can also compensate for the optical distortion produced by the water-to-air transition by learning the physical laws governing apparent target size and the fish's relative position to the target. Having such a generalizable "rule of fin" enables an archerfish to gauge absolute sizes of objects from unfamiliar angles and distances. I wonder if archerfish also practice entomology, visually identifying insects to know whether they are tasty, whether they are too big to eat or too small to bother with, or whether they sting.

Most likely, archerfish have been squirting water jets for at least as long as humans have been throwing stones, and I suspect that wrasses were using rocks to crack clams open long before our ancestors started bashing hot metal against anvils in the Iron Age. But can fishes spontaneously invent tool use, as we can when unexpected conditions require us to improvise? In May 2014 a study highlighted an example of innovative tool use by Atlantic cods being held in captivity for aquaculture research. Each fish wore a colored tag affixed to its back near the dorsal fin, which allowed the researchers to identify each individual fish. The holding tank had a self-feeder activated by a string with a loop at the end, and the fish soon learned they could release a morsel of food by grabbing the loop in their mouth and pulling on it.

Apparently some of the cods discovered they could activate the feeder by hooking the loop onto their tag and swimming a short distance away. These clever cods honed their technique through hundreds of "tests"—and it became a finely tuned series of goal-directed, coordinated movements. It also demonstrated true refinement because the innovators were able to grab the pellet a fraction of a second faster than by using their mouth to get the food. That fishes are routinely expected to interact with a foreign device to feed themselves is impressive enough but that some devised a new way of using their tag, in this case, shows a fish's capacity for flexibility and originality.

Tool use by fishes seems confined to a limited number of fish groups. Australian fish biologist Culum Brown suggests wrasses in particular may be fishes' answer to the primates among mammals and the corvids (crows, ravens, magpies and jays) among birds in having a greater than expected number of examples of tool use. It could just be that living underwater offers fewer opportunities for it than living on land. But we do know the tuskfish and the archerfish are prime examples of evolution's boundless capacity for problem solving, and they might turn out to have plenty of company among other fishes. SA

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MORE TO EXPLORE

The Use of Tools by Wrasses (Labridae). G. Bernardi in *Coral Reefs*, Vol. 31, No. 1, page 39; March 2012.

Innovative Behaviour in Fish: Atlantic Cod Can Learn to Use an External Tag to Manipulate a Self-Feeder. Sandie Millot et al. in *Animal Cognition*, Vol. 17, No. 3, pages 779–785; May 2014.

Competition Drives Sophisticated Hunting Skills of Archerfish in the Wild. Ingo Rischawy et al. in *Current Biology*, Vol. 25, No. 14, pages R595–R597; July 20, 2015.

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Brainy Birds

Chickens are smart, and they understand their world, which raises troubling questions about how they are treated on factory farms

By Carolynn "K-lynn" L. Smith and Sarah L. Zielinski

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IN THE ANIMAL KINGDOM, SOME CREATURES ARE SMARTER THAN OTHERS. BIRDS, in particular, exhibit many remarkable skills once thought to be restricted to humans: Magpies recognize their reflection in a mirror. New Caledonian crows construct tools and learn these skills from their elders. African grey parrots can count, categorize objects by color and shape, and learn to understand human words. And a sulfur-crested cockatoo named Snowball can dance to a beat. Few people think about the chicken as intelligent, however. In recent years, though, scientists have learned that this bird can be deceptive and cunning, that it possesses communication skills on par with those of some primates and that it uses sophisticated signals to convey its intentions. When making decisions, the chicken takes into account its own prior experience and knowledge surrounding the situation. It can solve complex problems and empathizes with individuals that are in danger.

These new insights into the chicken mind hint that certain complex cognitive abilities traditionally attributed to primates alone may be more widespread in the animal kingdom than previously thought. The findings also have ethical implications for how society treats farmed chickens: recognizing that chickens have these cognitive traits compels moral consideration of the conditions they endure as a result of production systems designed to make chicken meat and eggs as widely available and cheap as possible.

CHATTY CHICKENS

IT HAS TAKEN RESEARCHERS almost a century to figure out what is going on in the brains of chickens. The first inklings emerged from studies conducted in the 1920s, when Norwegian biologist Thorleif Schjelderup-Ebbe established that the birds have a dominance system, which he named the "pecking order" after noting that chickens will enforce their leadership by administering a sharp peck of the beak to underlings whenever they get ideas above their station.

The next major breakthrough in understanding the chicken mind came several decades later. The late Nicholas and Elsie Collias, both then at the University of California, Los Angeles, categorized the birds' calls and determined that chickens have a repertoire of about 24 different sounds, many of which seem to be specific to certain events. For example, when faced with a threat from above, such as a hungry eagle, the birds crouch and emit a very quiet, high-pitched "eeee." The clucking sound that most people associate with chickens is actually one they use when encountering a ground predator. The discovery of food elicits an excited series of "dock dock" sounds from males, especially when a judgmental female could be listening.

These early findings suggested that more happens in the chicken's walnut-size brain than one might think. The vocalizations appeared to encode specific information intended to evoke a particular response from onlookers. Yet connecting these sounds and movements with their true meaning proved difficult until the development, in the 1990s, of technology that allowed researchers to test their hypotheses more rigorously. It was then that the late Chris Evans of Macquarie University in Sydney, Australia, and others began to use digital audio-recording devices and high-resolution televisions to test the function of chickens' array of sounds under controlled conditions. In essence, they created a virtual reality for the birds, surrounding a test cage with TVs that allowed them to change what a chicken en-

IN BRIEF

Mounting evidence indicates that the common chicken is much smarter than it has been given credit for.

The birds are cunning, devious and capable of empathy. And they have sophisticated communication skills.

That chickens are so brainy hints that such intelligence is more common in the animal kingdom than once thought.

This emerging picture of the chicken mind also has ethical implications for how society treats farmed birds.

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FACTORY-FARMED CHICKENS, such as these hens on a farm in Fleurus, Belgium, often live in extremely crowded conditions.

countered—a companion, a competitor, a predator—and to record how it responded to a variety of situations. A test chicken might see a simulated hawk flying overhead, or a fox running toward it from the side, or a rooster making a series of dock-dock sounds.

This virtual reality led to a truly astonishing revelation: the sounds or movements an individual chicken makes convey specific information, and other chickens understand it. A chicken need not see an aerial predator, for instance, to behave as if one was there; it needs only to hear the warning call from another bird. The chickens' calls are "functionally referential," as behaviorists would say—meaning that they refer to specific objects and events broadly in the way that words used by people do. In a chicken hearing the calls, the sounds appear to create a mental picture of that particular object, prompting the bird to respond accordingly—whether to flee a predator or approach a food source.

The virtual world also revealed that individual chickens tailor their messages for their audience. A rooster that sees a threat overhead, for example, would make an alarm call if he knows a female is nearby, but he would remain silent in the presence of a rival male. Females are equally selective, only sending up an alarm when they have chicks.

Taken together, these findings suggested the sounds did not simply reflect a bird's internal state, such as "frightened" or "hungry." Instead the chickens interpreted the significance of events and responded not by simple reflex but with well-thought-out actions. Chickens, it seems, think before they act—a trait more typically associated with large-brained mammals than with birds.

BY HOOK OR BY CROOK

THE REFERENTIAL CALLS showed that chickens are more cognitively sophisticated than they have been given credit for. The research also raised an intriguing question: If these birds have the ability to communicate information about environmental events, might they also withhold that news or even broadcast misinformation when they stand to benefit from such deceitful behavior? Further insights have come from studies of other forms of chicken signaling.

Scientists have known since the 1940s that the birds perform complex visual displays in connection with the discovery of food. The most prominent of these displays is a series of actions collectively called tidbitting, in which an alpha rooster twitches his head rapidly from side to side and bobs it up and down, picking up and dropping food over and over again to signal to a female that he has found something tasty. This performance is the main way he lures a mate. Scientists thought the subordinate males, for their part, focus on keeping a low profile, so as to avoid attracting negative attention from the alpha. Yet some observations of chickens in their social groups hinted that the pecking order of the birds might not be quite as orderly as researchers initially thought. In fact, mounting evidence indicated that chickens could be devious bastards.

Human observers initially missed this underlying drama because interactions between members of the flock are short and often secretive; the birds prefer to hide in the tall grass and among the bushes. At the same time, it is just not possible for a single person to monitor all the chickens at the same time. To

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minimize those difficulties, one of us (Smith) came up with a solution she called "Chicken Big Brother."

Smith and her colleagues wired the outdoor aviaries at Macquarie University—large outdoor spaces with lots of vegetation, surrounded by nets on all sides—with multiple high-definition cameras and an array of microphones to catch every move and sound the birds made. They then analyzed the resulting recordings.

As expected, the alpha in any group would crow to show he was the master of the territory. He would perform the tidbitting display to attract the ladies. And he would make alarm calls to warn the flock of danger from above.

It was the subordinates that provided the twist. The team expected that these males should keep to themselves, to avoid the harassment of being chased, pecked and spurred by the alpha if they dared to make a play for his girl. Yet the cameras and microphones revealed a more complex story. These lesser males employed surreptitious tactics in a way previously thought impossible for the birds: they performed only the visual part of tidbitting—making the head motions without making the dock-dock sounds—thus creating a new signal that could quietly attract a mate while sidestepping the wrath of the alpha rooster.

The fact that the subordinate males modify the tidbitting signal in this way to secretly seduce the hens demonstrated a behavioral flexibility that shocked researchers. But they had yet to plumb the full depths of the birds' deviousness.

To examine the animals' behavior more closely, they added more technology to their tool kit. The chickens' vocalizations were often so subtle that Smith and the other researchers were unable to catch them, even with the extensive camera-and-microphone setup. They needed a way to record every call as it was made and heard by each of the individual chickens.

Ideally, they would outfit the chickens with little backpacks carrying lightweight wireless microphones similar to those reporters wear when working out in the field. But where to find the right materials for those packs? Bras, Smith thought, could do the trick. She began a hunt for old ones with easy-to-latch hooks and preferably colored black so they would not stand out against the feathers. Smith cut off the hooks and adjustable straps and attached these parts to the microphone to create a harness. Once strapped to a bird's waist, the jury-rigged apparatus—affectionately dubbed Chicken Big Brother 2.0—would record what the chicken said and heard.

Smith was particularly keen to take a closer look at how the animals respond to danger. The previous research showing that males would sometimes call out when they saw an aerial predator, such as a hawk, was puzzling because making those squeals would place the rooster at greater risk of getting noticed and attacked himself. Scientists had assumed that the male's need to protect his mate and offspring was so critical that making the call was worth the risk. Yet Smith wondered if other factors influence the calling behavior.

It turns out they do. Recordings from Chicken Big Brother 2.0 revealed that males sometimes made calls for selfish reasons. The birds monitored the danger to themselves and their rivals and were more likely to call if they could both minimize their own risk and increase a rival's. A male calls more often if he is safe under a bush and his rival is out in the open, at risk of being picked off by a swooping predator. If the rooster is lucky, he will protect his girl, and another guy will suffer the consequences.

FINDINGS

The Virtual Chicken Experiments

The knowledge that chickens will watch one another on television inspired one of us (Smith) and her colleagues to create a 3-D animated rooster using the same rendering technology employed in movies such as *Skyfall* and *Titanic*. This virtual rooster allowed the team to test the meaning of the birds' displays and their perceptions of one another. It also solved the age-old question of why roosters have wattles.

The wattle is that dangling flap of skin that hangs loosely from a rooster's beak. When a male performs his tidbitting display—a series of head movements that he uses to tell potential mates that he has found food—the wattle swings back and forth, even smacking him in the side of the head if he gets too enthusiastic.

Decades of research had failed to find any benefit to the male's having a wattle. Smith suspected that the flap of skin might make a male's tidbitting display more obvious and give him an edge in attracting the females, but she could not test her idea by cutting off the appendage and seeing how a female reacted. Instead she created an animated rooster that would tidbit on command for a live hen and then altered the flexibility and size of the wattle on her animated bird to test how the females would react.

The wattle, it turned out, acts like a red flag to the females, making it easier for a hen to spot the male that has the food. For the male, the ornament may cost him a bit in terms of his health because a bigger wattle comes with more testosterone, which weakens the immune system, but the cost is worth it in the long run because it gets him the girls.

Sometimes the chickens' intelligence made studying them challenging. On multiple occasions a bird would subvert an experiment by answering a different question than the one the researcher was posing. In a test of the tidbitting display, Smith had created a setup in which a hen got a chance to watch a video of a male with food. To do so, the female had to wait behind a door that had been rigged with a remote-controlled servo stripped from a toy car. One hen that wore an orange band with the numbers 07 (and thus affectionately dubbed "007") was notorious for getting into trouble. While waiting for the researcher to open the door via remote control, 007 grew impatient and began examining the release mechanism closely, turning her head from side to side. After a few moments, she carefully plucked the wire that controlled the latch. The door opened, and 007 got what she wanted: to be close to the guy and his food. After that single trial, she would never wait again. Although the researchers changed the latch configuration several times, 007 was always able to solve the puzzle and escape before her turn. —*C.L.S. and S.L.Z.*

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This strategy is known as risk compensation, and it is yet another skill that chickens have in common with humans. Many of us will take on more risk if we perceive a mitigating factor. People will drive faster when wearing a seat belt, for example, or when in a car equipped with antilock brakes. Male chickens will likewise take more risks if they feel more secure.

MOTHER HEN

THE CHICKEN'S LIST of cognitive skills continues to grow with each scientific discovery. Giorgio Vallortigara of the University of Trento in Italy has shown that young chicks have the ability to distinguish numbers and use geometry. Given a half-completed triangle, for example, chicks can identify what the shape should look like with all its parts. Chicks can learn patterns in sets of objects (when looking for food) or sounds and recognize these patterns again in the future. Such skills may underpin animals' ability to understand complex relationships between objects or individuals in their world and may help with foraging or navigation, for example. And research published in 2011 by Joanne Edgar of the University of Bristol in England and her colleagues revealed a softer side of these sometimes Machiavellian birds, demonstrating that they are capable of feeling empathy.

THE CHICKEN'S FLEXIBILITY AND ADAPTABILITY, DERIVED FROM ITS SOCIAL RED JUNGLEFOWL ANCESTOR, MAY HAVE BEEN PART OF ITS UNDOING.

In Edgar's experiment, mother hens watched as their chicks received a harmless puff of air that ruffled their downy plumage. The chicks perceived the puff as a threat and showed classic signs of stress, including increased heart rate and lowered eye temperature. Intriguingly, their mothers also became upset simply by observing their chicks' reaction. They showed the same signs of stress the chicks exhibited even though the hens themselves did not receive the puff of air and the chicks were in no obvious danger. The hens also made more clucking calls to their chicks. These findings indicate that chickens can take the perspective of other birds—an ability previously seen in only a handful of species, including ravens, squirrels and, of course, humans.

The fact that the common chicken, which is not closely related to other bird species known for their braininess, has such advanced cognition suggests something interesting about the origin of intelligence. Perhaps it is rather more common in the animal kingdom than researchers have thought, emerging whenever social conditions favor it as opposed to being a rare, difficult-to-evolve trait.

For its part, the chicken presumably inherited its cognitive prowess from its wild ancestor, the red junglefowl, which lives in the forests of southern and Southeast Asia. There the ancestral chicken society consisted of long-term, semistable groups of four to 13 individuals of varying ages. A dominant male and a dominant female headed each group, and as in many other societies, those in charge got what they wanted, whether it be food, space or sex, mostly by keeping their subordinates in line. Males spent much of their time strutting their stuff for the females and providing them with food; females carefully observed the males, judging them on their actions and remembering what each had done in the past; they shunned the ones that were deceptive or nasty. A rooster's reputation was important to his long-term success with the hens, and competition for the females was fierce.

Competition within the flock was not the only source of pressure on the birds' mental capacity. They also faced a range of threats from outside the flock—including predators such as foxes and hawks—each of which necessitated a different escape strategy. These conditions forced the fowl to develop clever strategies for dealing with one another and the dangers around them, as well as ways to communicate about all these situations. Those characteristics are still present in the domestic chicken.

That such abilities belong to animals that humans eat by the billions raises questions about how they are treated. Birds that would typically live in small flocks in the wild can be penned in with up to 50,000 others. A potential 10-year life span is shortened to a mere six weeks for chickens raised for meat. They are killed so young because these birds have been genetically selected for such fast growth that allowing them to become any older would subject them to heart disease, osteoporosis and broken bones. Egg layers fare little better, living only 18 months in a space about the size of a sheet of printer paper.

The chicken's flexibility and adaptability, derived from its social red junglefowl ancestor, may have been part of its undoing, letting the birds survive even under the unnatural and intense conditions in which humans now raise them. This type of farming will likely continue as long as most people are unconcerned about where their food comes from and unaware of chickens' remarkable nature.

Consumers have begun to effect change, however. In Europe and some U.S. states, such as California and Massachusetts, new laws are being passed that require improved housing conditions for egg-laying chickens, largely driven by buyer demand for better animal welfare, as well as healthier food. In Australia, producers now actually highlight the positive conditions under which they raise their animals, competing for a growing population of ethical consumers. Yet there is still more to be done. The conditions under which meat chickens are raised have largely gone unscrutinized.

Researchers have just begun to elucidate the true nature of chicken intelligence, but one thing is already certain: these birds are hardly the "dumb clucks" people once thought them to be. SA

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MORE TO EXPLORE

Origins of Knowledge: Insights from Precocial Species. Elisabetta Versace and Giorgio Vallortigara in *Frontiers in Behavioural Neuroscience*. Published online December 9, 2015. Available at http://journal.frontiersin.org

A Chicken for Every Pot: The Economics, Evolution and Ethics of the Modern Chicken. Carolynn L. Smith in *Australian Zoologist* (Royal Zoological Society of New South Wales). Published online September 15, 2016.

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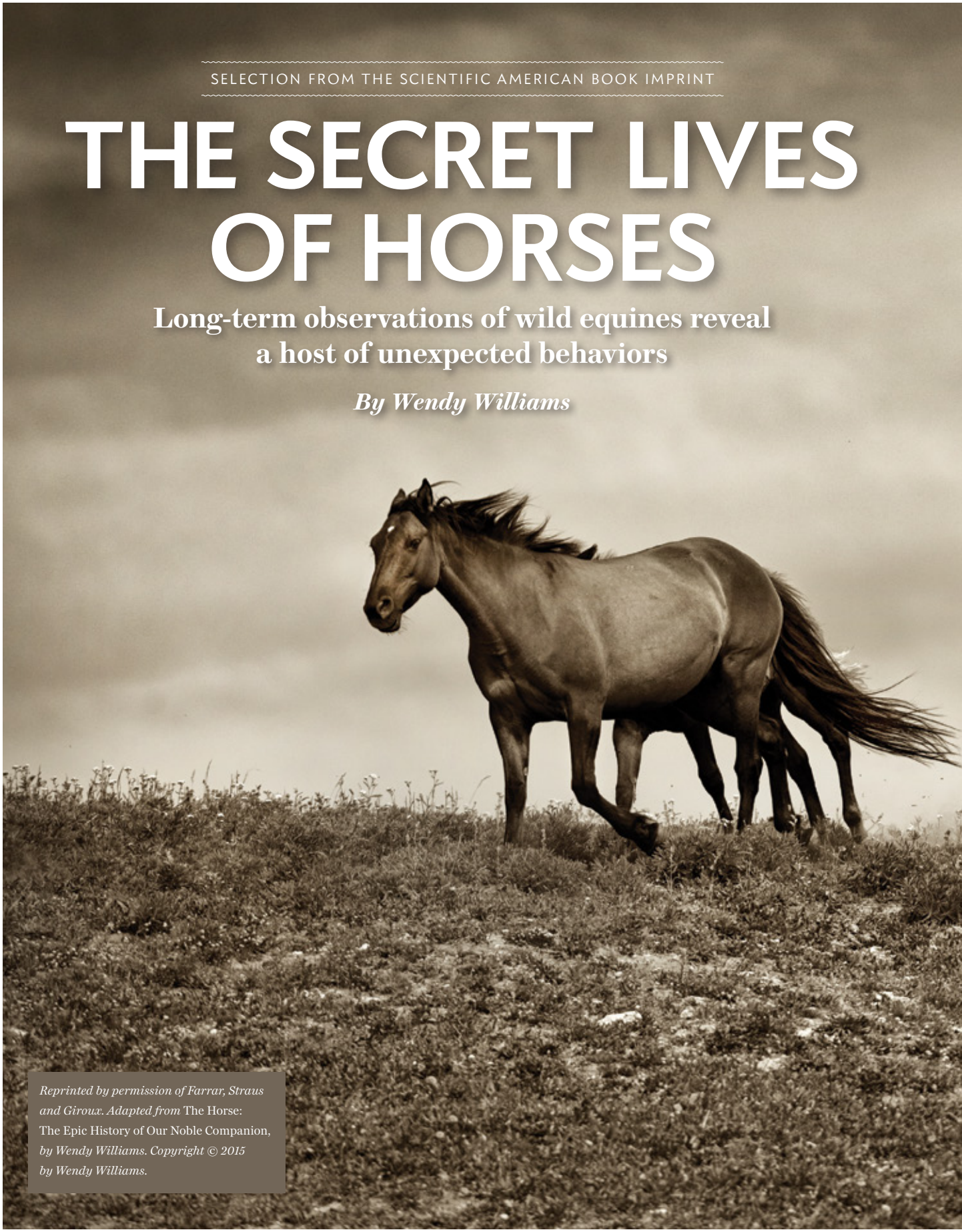
SELECTION FROM THE SCIENTIFIC AMERICAN BOOK IMPRINT

THE SECRET LIVES OF HORSES

Long-term observations of wild equines reveal a host of unexpected behaviors

By Wendy Williams



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WILD AT HEART: Untamed horses roam free in the Pryor Mountains of Montana.

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SOME TIME AROUND 35,000 YEARS AGO, WHEN MUCH OF EUROPE WAS LOCKED up in sheets of ice, an artist acquired a bit of mammoth ivory and began carving. A masterpiece emerged in the form of a two-inch-long horse. Its magnificently arched stallion's neck combines muscular potency and natural grace. Its head, slightly cocked, gives the animal an air of deep contemplation. One can almost hear him snort and see him toss his head, warning rivals to take care. No one knows who created this miniature marvel, dubbed the "Vogelherd horse" after the cave in Germany in which it was found, but it is clear that this ivory carver spent a lot of time watching wild horses, studying their social interactions and learning their body language.

Sadly, in the modern world, this pastime became something of a lost art. Equine scientists have studied the best way to train show horses, the best way to feed racehorses, the best way to heal the delicate bones in a lame horse's feet. But in contrast to the behaviors of wild chimpanzees, whales and elephants, among other species, the natural ways of horses have rarely garnered scientific interest. And of the few studies that were done, very few were long-term projects.

Recent efforts have begun to fill that gap—with surprising results. Scientists have documented behaviors among free-ranging horses that upend many long-held ideas about how these animals bond and interact with one another.

MARES VS. STALLIONS

HORSES ARE UNUSUAL among hoofed mammals. Many members of this group typically roam in large herds, seeking safety in numbers. Wild horses, in contrast, live year-round in small groups, or bands, of three to 10 individuals. Closely allied mares and their young offspring form the core of the band.

Members of a horse band are not simply group animals with ganglike mentalities. Researchers have found that, as with humans, individual bonds within bands may be more important than group identity. These bonds are sometimes based on family ties, but often they are just based on individual preference. These preferences can and do change: friendships come and go, foals grow up and depart to live elsewhere, male-female relationships sometimes work out and sometimes don't. As a result, the social lives of horses are nothing if not tumultuous. Indeed, long-term observation of these animals in the wild is like following a soap opera. There is a constant undercurrent of arguing, of jockeying for position and power, of battling over personal space, of loyalty and betrayal.

The latest ethological investigations—which is to say, objective studies of behavior under natural conditions—show that these power dynamics are more complicated than previously thought. The conventional view, as described in a recent National Academy of Sciences report, is that "a harem, also known as a band, consists of a dominant stallion, subordinate adult males and females, and offspring." At first glance, this assessment would seem to be true: what people notice when watching wild horses is the uproar created by the stallions. But research by Jason Ransom of Colorado State University and others has shown that this male-centric view is wrong. Far from being subordinate, mares frequently initiate the band's activities. The stallions are quite often little more than hangers-on.

Ransom was once watching a band of mares that stopped grazing and began heading for water. The stallion didn't notice. When he looked up and saw his female companions leaving, he panicked. "He started running after them," Ransom told me. "He was like a little boy calling out, 'Hey, where's everybody going?'" The mares ignored him. Whether the stallion caught up or not didn't appear to concern them.

Mares also sometimes have stallion preferences. They resist males they don't like with surprising persistence, even when that male has established himself as the band's stallion. Joel Berger, now at Warner College of Natural Resources, studied the behavior of two nonrelated mares that had spent several years together. The pair joined a band that was then taken over by a new stallion that asserted himself by attempting to copulate with them forcibly on numerous occasions. The mares refused his attentions and repeatedly aided one another by kicking and biting the stallion as he tried to mate, Berger observed in *Wild Horses of the Great Basin*. It's long been known that female elephants cooperate, but before ethologists began systematically studying free-roaming hors-

IN BRIEF

Scientists have long studied the best ways to train and treat domesticated horses, but they largely ignored the behavior of free-ranging horses. Recent research has begun to fill that gap.

Observations from long-term studies of wild horses show that the conventional, male-centric view of their power dynamics is wrong.

In fact, females often call the shots, employing tactics such as cooperation and persistence to get their way.

PRECEDING PAGES: LISA DEARING

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es, few people suspected that cooperating mares were capable not only of waging such a fight—but of winning it. Given the truth about mares, "harem" seems like such an old-fashioned word.

Fending off unwanted suitors is not the only means by which mares rebel. For years Laura Lagos and Felipe Bárcena, both at the University of Santiago de Compostela in Spain, have been studying the behavior of Garranos, an unusual type of free-roaming horse. Garranos live rough, tough lives in the rugged hills of northwestern Spain and northern Portugal, where they are under constant threat from wolves. In the course of their work, Lagos and Bárcena catalogued the behavior of a pair of mares in one band that were strongly bonded with each other and that often stood just a bit apart from the rest of the band.

At breeding time, the mares went together to visit the stallion of another band. Lagos watched one of the mares consort with this stallion rather than with the stallion from her own band. Then the mares returned to their original group. When the second mare was ready to breed, the duo again deserted their original band and its stallion to consort with the other stallion. Then, again, they returned to their original group. This was not an anomaly. The mares did the same thing the following year. "They prefer their own territory, but the stallion of the other band," she told me.

PERSISTENCE PREVAILS

UNTIL SCIENTISTS applied ethological research techniques to horses, few observers believed mares to be capable of such subtle deceit. They just weren't looking closely enough. It turns out that, unlike stallions, mares do not need to have huge fights to get what they want. Instead they use the technique of persistence. By way of example, Ransom tells the story of High Tail, a plain-Jane mare with a sagging back and poor coat. High Tail, so named because the dock of her tail sat a bit too high on her croup, is part of a population of wild horses that roam the Pryor Mountains in the American West. If you didn't know her life story, you could easily mistake her for a child's riding pony or a retired plow horse. With her glory days clearly over, you probably wouldn't give her a second glance. Yet Ransom's data showed that this mare had had a rich and varied life that involved a number of long-term male associates of her choosing.

Ransom first caught up with High Tail in 2003. The mare was passing her days in the company of Sam, a stallion born in 1991. Ransom thinks the two probably encountered each other during the wanderings of their youth. They stayed together for years. Eventually other mares joined them, forming a band. Research shows that roughly half the time mares and stallions bond in this peaceful fashion. There's no need for a stallion to "conquer" the mare; she is often a more than willing partner.

Shortly after Ransom began following High Tail and Sam's band, he noticed a second young stallion hanging around a short distance away. Sam did not welcome this new stallion, dubbed "Sitting Bull." The more Sitting Bull tried to become part of the group, the more Sam fought him off. Sam spent a good deal of energy trying to drive away the younger stallion but to no avail.

Whenever Ransom saw High Tail's band during this period, Sitting Bull was usually there, hanging around on the outskirts, stalking the mares and dogging Sam, waiting for his chance to take over. The scientific literature contains accounts of satellite stallions learning how to cooperate with the lead stallion and thus gradually gaining the ability, on a limited basis, to mate with some mares, but this was not the case with Sam and Sitting Bull. The two fought continuously. Still, Sitting Bull stayed near, biding his time.

His chance came in 2004. Horses that live at the base of the Pryor Mountains constantly face the challenge of finding freshwater. High Tail's band often descended the steep walls of the Bighorn Canyon gorge, where they could drink their fill. One day they went down as a group. Sam did not allow Sitting Bull to come along. While the young stallion waited above, the rest of the horses stood on a small ledge and drank. Off in the distance heavy rains broke out. A flash flood inundated the gorge, cutting off the animals' escape route. For about two weeks High Tail and her band, along with Sam, remained trapped without food.

Realizing that the situation was dire, people intervened and helped them escape. The severely emaciated animals managed to climb up out of the gorge. Sam in particular had lost his muscular physique. Almost dead from starvation, he was easy pickings for Sitting Bull, who had hung around above the gorge. When the horses came up, Sitting Bull "just swooped right in and drove Sam off," Ransom says. Sam tried repeatedly to repel his younger competitor, but he was no longer strong enough.

Most of the band accepted the young stallion. Not High Tail. At every opportunity she left her band and headed off in search of her longtime mate, Sam. Each time she left, Sitting Bull chased her back, snaking his head and baring his teeth to threaten her with injury. To avoid being bitten, she complied and returned to the band, but the next time Sitting Bull failed to pay attention, High Tail took off again. This went on for many weeks until the younger stallion gave up chasing her. "From then on it was just Sam and High Tail," Ransom says. "They got their weight back, and at first Sam tried to drive Sitting Bull off and get back with the other mares, but each time he tried, he failed."

High Tail stayed with Sam until he died in 2010. (Because of the stress of constant fighting with other males, stallions often live much shorter lives than mares.) After Sam's death, researchers saw High Tail with a stallion they called Admiral. Eventually Admiral fell out of favor with her. Ransom doesn't know why.

We saw High Tail one afternoon that July. She was with two other horses. One was a mare from her original band, an animal she had known for years. The other was Sitting Bull. Rejected by High Tail in her younger years, he was now one of her boon companions. Primate field researchers long ago discovered the ebb and flow of alliances within primate troops, but until recently no one has watched horses in the wild closely enough to understand that they, too, behave this way. I asked Ransom if he thought there were any hard and fast rules about horse behavior in the wild. "They rarely choose to be alone," he replied. SA

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MORE TO EXPLORE

Wild Horses of the Great Basin: Social Competition and Population Size. Joel Berger. University of Chicago Press, 1986.

The Importance of Ethology in Understanding the Behavior of the Horse. D. Goodwin in *Equine Veterinary Journal*, Vol. 31, No. S28, pages 15–19; April 1999.

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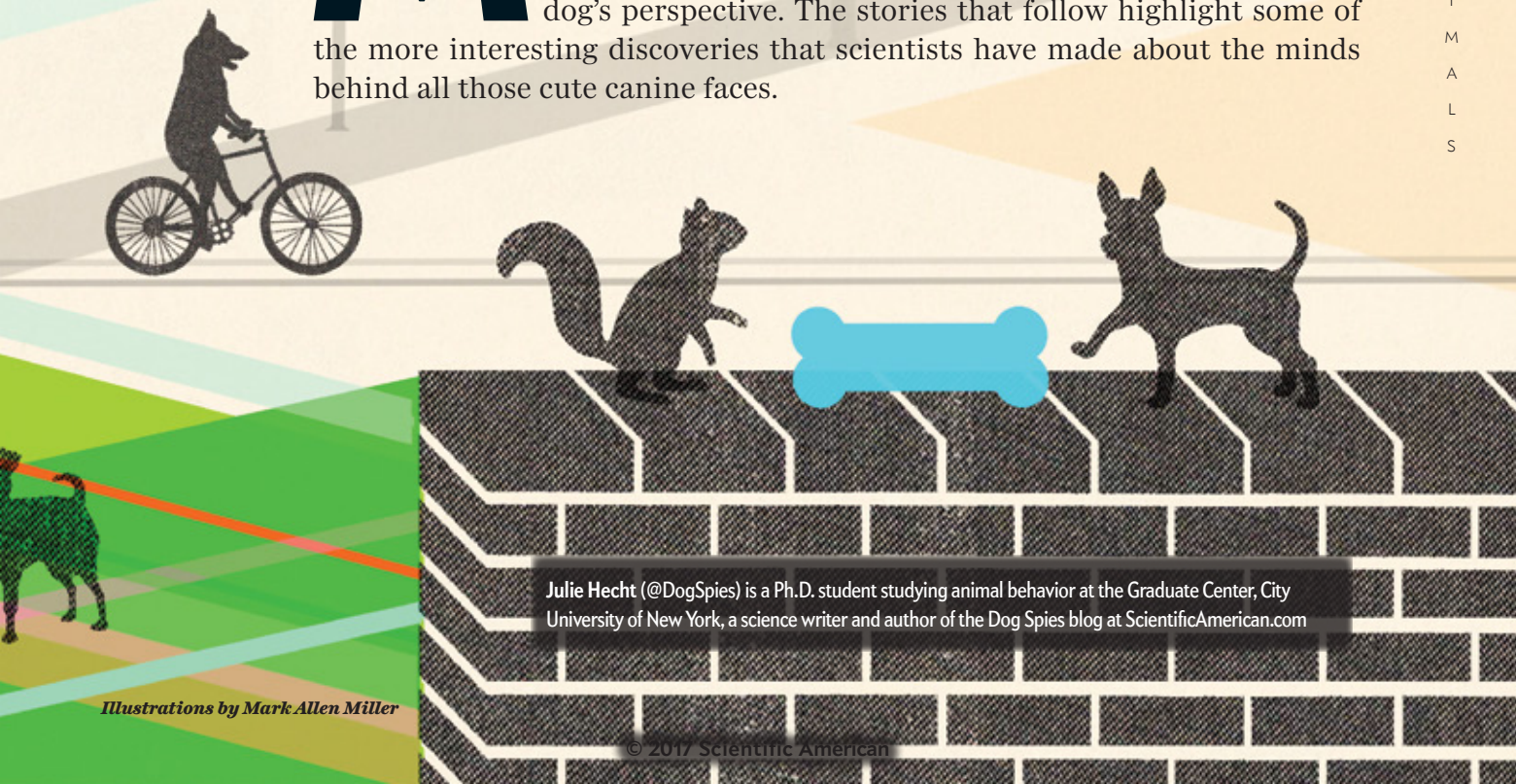
The World According to Dogs

Scientific findings uncover what our best friends know, why they do what they do and how to keep them happy

By Julie Hecht

MOST OF US DO NOT UNDERSTAND DOGS AS WELL AS WE think we do. We assume we know things, but we often rely on old theories and frequently do not look at actual dog behavior. Instead we should try to think about life from the dog's perspective. The stories that follow highlight some of the more interesting discoveries that scientists have made about the minds behind all those cute canine faces.



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Illustrations by Mark Allen Miller

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The Meaning of Belly-Up

When a dog rolls onto its back during play, does the maneuver indicate submission, akin to a person crying "uncle," or does it signify something else altogether? A study by Kerri Norman at the University of Lethbridge in Alberta, and colleagues there and at the University of South Africa, comes down on the side of "something else." Their report appeared in 2015 in an issue of *Behavioural Processes* devoted to canine behavior.

Investigating what behaviors mean during dog-dog play is not new. For example, you have probably heard of play signals that help dogs to clarify play from not play. These signals indicate something like, "Hey, when I just bit you in the face, I didn't mean it like 'I'M BITING YOU IN THE FACE.' It was just for fun. See! Here's a play bow for additional clarity. All fun here!" Play signals may also include exaggerated, bouncy movements or presentation of a "play face"; they start or maintain play, and they occur around potentially ambiguous behaviors—such as a bite, tackle or mount—or anything that might be misconstrued as not playing. But not all behaviors that appear during play between dogs are as well studied.

Outside of play, rolling onto one's back is often seen as a submissive gesture that curtails or avoids aggression by another dog. In a classic 1967 paper in *American Zoologist,* Rudolf Schenkel of the University of Basel in Switzerland describes this so-called passive submission as expressing "some kind of timidity and helplessness," like coming out with your hands up or waving a white flag.

Some have suggested that the rollover performed in dog-dog play is about preventing aggression. Owners observing playing dogs from the sidelines often take this a step further—the dog spending more time on its back is labeled "submissive" or "subordinate," whereas the dog on the top is "dominant."

But what if rolling over means something different during play? Norman and her colleagues wanted to know whether "rolling over onto the back and adopting a supine position" during play is an "act of submission" and serves to stop the interaction or hinder subsequent aggression. Or, they speculated, it might be essentially playful, "executed tactically, for combat purposes," to encourage play, avoid a play bite (defensive maneuver) or deliver a play bite (offensive maneuver).

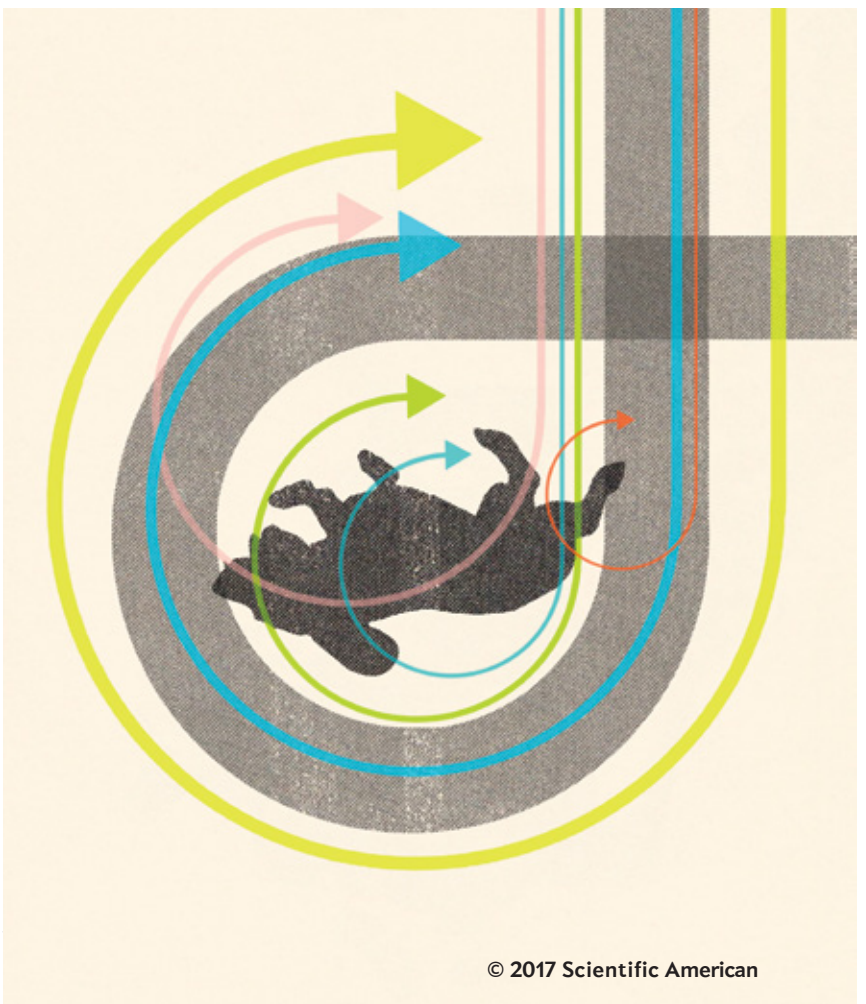
The researchers collected data in two contexts: staged play sessions where a medium-sized female dog was paired with 33 new play partners of various breeds and sizes, and 20 YouTube videos where two dogs played together—half the videos paired similarly sized dogs, and the other half had dogs of different relative sizes.

Not all observed dogs rolled over during play, particularly in the staged play sessions, where only nine partners rolled over when playing. In the YouTube videos, 27 of the 40 dogs rolled over, and it occurred in both similarly sized and differently sized pairs. If your dog is not a roller during play, he is in good company.

For dogs that did roll over, what did it mean? The researchers examined all instances of the behavior to see whether rollovers were associated with submission—decreasing play, remaining passive, or being performed by the "smaller or weaker" partner—or were instead associated with the interactive, fun, combative nature of play, where rollovers preceded "launching an attack (offensive), evading a nape bite (defensive), rolling in front of a potential partner (solicitation) or rolling over in a nonsocial context (other)."

The findings are stark: the smaller of the two play partners was not more likely to roll over than the larger dog. Additionally, "most rollovers were defensive and none of the 248 rollovers was submissive." Most in-play rollovers in the study, the researchers found, were part of *play* fighting (meaning the fighting was itself playful, not *real* fighting).

But could it be that once dogs are on their back, submission kicks in? For example, a dog could go on its back to avoid a neck bite and then lie motionless, suggestive of passive submission. But that is not what the dogs did. Instead once on their back, dogs in the supine position both blocked playful bites



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and launched them at their partner.

Another way to think about rolling over in play is as a self-handicapping behavior that helps dogs of different sizes or sociabilities play together. Self-handicapping is instrumental to play, and it implies that a dog is tempering its behavior. For example, during play, dogs do not deliver bites at full force, and a larger dog might roll over to allow a smaller dog to jump on or mouth it. Some dogs will even use this behavior to invite bites and solicit play from another dog.

It is not safe, then, to assume that a dog sliding onto its back during play is essentially saying, "YOU CAME ON TOO STRONG" or "OKAY, YOU WON THIS ROUND!" In some contexts, this posture is certainly associated with fear or with defusing or preventing aggression, but the recent study reminds us that rolling over, as with many behaviors, does not have a single, universal meaning. Instead it is often just playful.

When a Dog Won't Play

YOU HAVE PROBABLY HEARD THE EXPRESSION, "Life is short: play with your dog." "Okay!" you think, "I'll do it!" After all, dogs play together until they are exhausted. They also play with people, although good play is not always a given. Have you ever tried to play with a dog, and it just doesn't work? "The dog's not playing right," you may think. "This stinks."

Don't be so quick to blame the dog. Research suggests that it might be *you* who is not "playing right."

In 2001 animal welfare and behavior researcher Nicola Rooney, now at the University of Bristol in England, and her colleagues wanted to know whether dogs respond to people's play signals. In the study, volunteers played with their dog for five minutes in the comfort of their home, and the sessions were videotaped. Owners were asked to engage with their dog "as they usually did," but here is the key: they were not allowed to use objects or toys.

After the sessions, the researchers watched the videos and noted which behaviors owners used to initiate or maintain play. They identified 35 common play signals, including patting the floor, clapping, shoving, hitting or tapping the dog and, of course, play bowing. People also blew at dogs, barked at them and grabbed their paws. And who can forget my favorite behavior, "hand spider," where the "person moved their hand or fingers simulating movement of an insect or other creature."

Did dog owners' play signals instigate play? And more specifically, did the commonly used signals elicit play more often than the rarely used ones?

Of the 35 most common play signals, Rooney and her colleagues found that a signal's popularity "was not related to its success at initiating or sustaining play." For example, patting the floor was used most often, but play followed only 38 percent of the time. Other not so successful but commonly used invitations included scruffing the dog and clapping. Some things people did, including picking up or kissing the dog, failed to elicit play during any of the sessions.

All is not lost! A few behaviors were incredibly successful. The researchers found that giving chase and running away and lunging forward were associated with play 100 percent of the time. Signaling "up" (tapping one's chest to entice the dog to jump up), grabbing or holding a dog's paws, and play bowing also got great results.

The study's conclusion is somewhat somber: "We suggest that humans often use ineffective [play] signals." Instead of blaming dogs for not playing right, people could evaluate the effects of their own actions, acknowledging that certain signals are better at eliciting play than others.

Alexandra Protopopova, now at the Human-Animal Interaction Lab at Texas Tech University, and her colleagues at Arizona State University Canine Science Collaboratory have highlighted a sad consequence of inept play signaling by humans: it can sabotage adoption of a dog from a shelter. The team found that when a potential adopter takes out a shelter dog for a one-on-one meet and greet, only two behavioral variables predicted whether that dog was leaving the shelter: lying in close proximity to the person and responding to the person's play solicitation. Dogs lying close to the person were about 14 times more likely to be adopted, and a dog who ignored a person's play initiation was unlikely to be adopted.

INSTEAD OF BLAMING DOGS FOR NOT PLAYING RIGHT, PEOPLE COULD LOOK AT THEIR OWN BEHAVIOR AND EVALUATE ITS EFFECT, ACKNOWLEDGING THAT CERTAIN PLAY SIGNALS ARE MORE EFFECTIVE AT ELICITING PLAY THAN OTHERS.

Taken together, these two studies paint a potentially scary picture for shelter dogs: people do not always use play signals that result in play, but people are unlikely to adopt a dog that does not respond to their signals. Nobody wins.

A subsequent study by Protopopova and her colleagues found that when potential adopters were explicitly told to play with a dog's preferred toy, not only did social play increase, but so, too, did adoption rate.

When I think about dogs in a shelter going up for their one-on-one interviews, I hope potential adopters cut them some slack and do not blame the dogs if they do not grasp overtures for play. The list of factors that could contribute to whether a dog will play with a new, strange human it just met is endless. On top of that, the shelter environment is often a weird, chaotic place, not exactly hospitable to having a fun time.

When meeting a dog for the first time, go slowly and keep your expectations in check. For shelter dogs, as with speed dating, a lot is riding on the first encounter. Reflect on your play behaviors just as much as you think about theirs.

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Is That Really Guilt You See?

LIVE WITH A DOG, AND YOU have most likely met the "guilty look." You come home. The plants are knocked over, and soil is tracked all over the floor. The dog is abnormally still and averts its gaze as it thumps its tail slowly.

But does the dog feel responsible for the mess and sorry about having disobeyed your rules? That is hard to say. Research to date, including an open-access study published in 2015, suggests that the answer is no. Moreover, the findings reveal that scolding or punishing dogs will not necessarily decrease unwanted behavior.

Owners asked to describe a dog's guilty look comment that, in addition to potentially freezing, looking away and thumping their tails, the dog may try to look smaller and assume a nonthreatening pose. Some might lift a paw or approach the owner in a low posture. Others retreat.

It is tempting to think that if a dog acts much as we do when we feel guilty, then the dog must also understand that its behavior was wrong and feel guilty. Yet these are the same actions that animal behavior researchers and experts describe as reflective of submission, appeasement, anxiety or fear. Such displays are employed by social species, such as dogs and wild gray wolves, in many different contexts to reduce conflict, diffuse tension and reinforce social bonds.

When we investigators create experiments to better understand dogs' conceptual frameworks, we often find that although their actions might look much like those of people, their understanding of the situation might differ. In this case, it is possible that rather than guilt operating when your dog puts on a "guilty face," the pooch may actually be experiencing general anxiety or fear or a desire to avoid being on the wrong end of your anger or frustration.

In 2009 Alexandra Horowitz of Barnard College (and author of *Inside of a Dog: What Dogs See, Smell, and Know*) published a study in *Behavioural Processes* that explored the events preceding the seemingly guilty look. By varying both the dog's behavior (either eating or not eating a disallowed treat) and the owner's behavior (either scolding or not scolding), she was able to isolate what the look was associated with. She found that it did not appear more when the dogs had done something wrong. Instead it popped out in full form when the owner scolded. Horowitz further found that when dogs were reprimanded, the most exaggerated guilty look was displayed by the dogs that had not eaten the treat but were reprimanded anyway (because the owner thought the dog had eaten it). That means, for example, that in a multidog household, a dog could easily look guilty without ever having transgressed.

SCOLDING A GUILTY-LOOKING DOG AFTER THE FACT COULD GIVE YOU A FALSE SENSE OF MUTUAL UNDERSTANDING AND THE INCORRECT BELIEF THAT YOU ARE PUNISHING THE BAD BEHAVIOR EFFECTIVELY.

I found a similar result in a follow-up experiment that I conducted with Ádám Miklósi and Márta Gácsi of the Family Dog Project at Eötvös Loránd University in Budapest and published in 2012 in *Applied Animal Behaviour Science*. Dogs had the opportunity to break a rule (that food on a table is for humans and not dogs) while owners were out of the room. When the owners returned, dogs that ate were not more likely to look guilty than those that abstained. In this context, the guilty look was not present without a scolding owner. We also looked at whether owners are better able than others to tell when their dogs have been disobedient. Owners who had seen their companions adhere to the rule were not better at identifying that the dogs had transgressed in their absence.

"But wait!" the peanut gallery cries. "I have seen my dog act guilty *before* it is scolded." Owners often do interpret such behavior to mean that dogs "know" they have done wrong. This is a complicated issue, but findings to date suggest that dogs engage in guilty-seeming behavior when they sense that something will elicit an owner's displeasure and hope to avoid a breach in the relationship.

Ljerka Ostojić and Nicola Clayton of the University of Cambridge and Mladenka Tkalčić of the University of Rijeka in Croatia reported in 2015 in an open-access article in *Behavioural Processes* on whether a dog's guilty look could be triggered by environmental cues, such as the disappearance of a forbidden food. By using a manipulation somewhat similar to that of Horowitz, Ostojić and her colleagues found that the guilty look was not affected by the dog's own behavior (either eating or not eating the food) or whether the food was present or absent. In their experimental context, dogs did not display the guilty look in the absence of a scolding owner.

At the same time, the study does not exclude the possibility that in the home environment, owners may very well observe the infamous look prior to scolding. In the late 1970s a veterinarian in Wisconsin published a paper offering a clear example of fear masquerading as guilt. A dog called Nicki had taken to shredding paper in the owner's absence. To see if the dog's guilty-seeming behavior actually stemmed from guilt, the veterinarian had the owner shred paper, leave the house and return home. When the owner came back, Nicki looked "guilty," even though she had done nothing wrong. Dogs are incredibly sensitive to environmental and social cues. In this case, the dog apparently viewed the paper on the floor as a sign of a scolding to come.

"Evidence + Owner = Trouble," explains primatologist Frans de Waal, in *Good Natured: The Origins of Right and Wrong in Humans and Other Animals*. As a social species aiming to maintain relationships, dogs could show submissive displays before an owner scolds without the behavior indicating an apology or admittance of guilt. Instead these displays can aim to appease or pacify. And they certainly could have that effect: in one study, I found that nearly 60 percent of owners surveyed on a questionnaire reported that the "guilty look" led them to scold their dog less.

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You may wonder why I and others harp on the misattribution of a sense of guilt in dogs. As I have said online in The Dodo, this is an issue about dog welfare: "When you get angry or forgive your 'guilty' dog for demolishing your house, you ignore deeper concerns that, if addressed, could reduce or eliminate those behavior problems. Was the dog bored? Scared? Anxious? Did something change in your routine that confused it? Sadly, scolding dogs often does not decrease future undesirable behavior. If anything, the 'guilty look' could just become more exaggerated over time as your confused companion enters an anxious cycle of destruction and appeasement."

Even worse, scolding a guilty-looking dog after the fact could give you a false sense of mutual understanding and the incorrect belief that you are punishing the bad behavior effectively. A punishment, by definition, decreases the behavior in the future. Unfortunately, studies find that scolding a "disobedient" dog, especially after it misbehaves, does not lead to a notable decrease in the "bad" behavior. A study from the late 1960s found that dogs reprimanded just 15 seconds after performing a "disallowed" behavior not only continued to perform the behavior in the future but did so while showing notable appeasement and fear-related behaviors.

Berateament after the fact does not work, and the guilty look is better interpreted as fear or appeasement. Best to just clean up the mess and think about how to avoid it in the future.

NO GUARANTEES

Does Your Pooch Love You?

The answer may surprise you

By Jason G. Goldman

You love your dog. Does your dog love you back? A group of Swedish and Danish researchers went looking for an answer. More specifically, knowing that dogs are highly attuned to cues from humans, the researchers suspected that dogs belonging to owners who felt they had a great relationship with their pets would also perceive that the relationship was close, perhaps because the owners' attitude would lead to a high frequency of positive interactions between the duo.

Twenty dog-owner pairs participated in the study, which was led by Therese Rehn of the Swedish University of Agricultural Sciences and published in the January 2014 issue of *Applied Animal Behaviour Science*. The humans all completed a questionnaire called the Monash Dog Owner Relationship Scale (MDORS), which was designed to evaluate the strength of the relationship from the perspective of the owner. The MDORS contains 28 items divided into three subscales. The first subscale assesses the nature of the dog-owner interactions ("How often do you hug your dog?"), the second reflects the emotional closeness that the owner feels toward his or her dog ("I wish my dog and I never had to be apart"), and the third concerns the perceived investment required to care for a dog ("My dog costs too much money").

The dogs were thrust into a modified version of the Ainsworth "strange situation" procedure, a clever experiment originally designed to measure the strength of human parent-child relationships. It centers on a child—or dog—being left alone with a stranger. The doggy version begins with the owner sitting in a chair ignoring the dog. After a few minutes, a stranger comes into the room and, ignoring the dog, talks to the owner. The stranger attempts to play with the dog, and then the owner quietly leaves the room. The stranger continues to engage the dog in play and then exits, leaving the dog alone. The owner returns, greets the dog and begins ignoring it again. The stranger returns, greets the dog and ignores it as well. Finally, the owner leaves once more.

When conducted with human toddlers, the slightly distressing nature of the strange situation activates an innate, adaptive system that motivates the child to seek comfort from the parent. By carefully observing the children and weighing their comfort-seeking behaviors against their more independent exploration behaviors, researchers can determine whether or not children have secure emotional attachments to their parents. Children who feel more securely attached are more likely to seek closeness with Mom or Dad when stressed but also to play independently once they feel comfortable.

The researchers predicted that canines whose owners perceived their relationship with their pets to be strongest would behave in ways indicative of strong bonding during the test. Instead they found only two significant correlations. When dogs were reunited with their owners after being alone, those whose owners reported having a lot of interactions with the animals sought out such interactions more—which might look like strong attachment but could equally have been a reflection of past rewards for initiating physical contact. And unlike securely attached toddlers, canines of such owners were less likely than others to play independently in the strange situation. In that way, they resembled insecurely attached youngsters. Dogs are not children, though, and did not show the separation anxiety that insecurely attached children display; thus, the latter finding is hard to interpret.

This study marks one of the first attempts to scientifically probe the connection between dogs' perceptions of their bond with their owners and owners' perceptions of their bond with their dogs. And here's the bad news for all those dog lovers who are just certain that Fluffy loves them back: there was no correlation between the "perceived emotional closeness" subscale of the MDORS questionnaire and the dogs' behavior in the strange situation. The researchers put it bluntly: "There was no evidence to support the view that because a person has a strong emotional bond to their dog, their dog is similarly attached to them." You cannot simply love a dog so much that it will be forced to love you back.

Jason G. Goldman (@jgold85) is a science journalist based in Los Angeles.

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Why Dogs Like People

DO YOU EVER WONDER WHAT MAKES some dogs *so* into us? Why at any moment Pluto might propel himself into Mickey's arms, giving Mickey a full-on scrub down with his tongue? Why some dogs want to meet everybody, whereas others would prefer you stay right where you are?

A 2014 study published in *PLOS ONE* by researchers led by Anna Kis and Melinda Bence, then at the Family Dog Project at Eötvös Loránd University in Budapest, and others used a novel method to explore the role that oxytocin plays in dogs' sociability toward humans.

Maybe you have heard oxytocin described as the "love hormone" because of its involvement in social interactions, stress relief and feelings of connectedness with other people. Spend time petting your dog, scratching Pluto's body and ears, and you are both apt to see increases in the oxytocin levels in your blood, indicating a positive experience for you both. Yet oxytocin is also not simple. Science writer Ed Yong points out in a 2012 Slate article: "The 'love hormone' fosters trust and generosity in some situations but envy and bias in others, and it can produce opposite effects in different people." Part of the story could be that variations in the gene that codes for the oxytocin receptor—the molecule that oxytocin binds to on nerve cells in the brain—mediate differences in social behavior.

To investigate whether Pluto's exuberance for Mickey and "people" in general is somehow associated with Pluto's genes, Kis and her colleagues took the following approach:

Step 1. Get to know the dog oxytocin receptor (*OXTR*) gene. For this study, the researchers selected dogs from two popular breeds, German shepherds and Border collies, and extracted DNA by swabbing the insides of their cheeks. This process ultimately identified three variations of the *OXTR* gene, each of which comes in two forms, with the forms seemingly having different effects on behavior. The three variations, or "polymorphisms," have the incredibly easy names of *–212AG, 19131AG* and *rs8679684*.

Step 2. Get a sense of how the dogs interact with people. More than 200 German shepherds and Border collies living as pets participated in a series of interactions with people. The tests investigated how dogs greeted both a known and an unknown person, how dogs responded to a stranger approaching in a threatening manner, and how dogs responded when their owner hid behind a large tree.

Step 3. Bring dog genes and dog behavior together. The researchers examined whether there was a relation between the *OXTR* polymorphisms and the way the dogs interacted with people during the social tests. They were particularly interested in how readily dogs approached people, as well as the canines' level of friendliness.

Describing the results, Kis says that "the way dogs behave toward humans, at least among German shepherds and Border collies, is influenced by the oxytocin receptor gene." For example, when it came to the *–212AG* gene, both German shepherds and Border collies carrying the form, or allele, known as *G* showed less interest in being around people than did those with the allele called *A,* suggesting the effect was the same in both breeds.

Yet analysis of the genes *19131AG* and *rs8679684* revealed opposite trends in the two breeds. For example, in the *19131AG* polymorphism, the investigators report, "the presence of the *A* allele, as opposed to the *G* allele, was associated with higher friendliness scores in German Shepherds and lower friendliness scores in Border Collies." This opposite effect suggests that "other genetic and cellular mechanisms (unexplored in the present study) might play a role in the regulation of this behavior besides our candidate gene."

Overall, then, the study indicates that dog sociability toward people is related to the varieties in the *OXTR* gene they possess but that oxytocin is "part of a bigger system" contributing to dogs' feelings toward humans.

Next up for this line of research: replication and the exploration of possible molecular interactions that account for the effects that particular oxytocin receptor variants have on dogs' behavior toward people.

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What Barks Say

ALTHOUGH AT TIMES YOUR DOG MAKES vocalizations that might be unwelcome, those sounds carry much information and meaning. In recent years many studies have investigated the noises made by companion dogs.

One major finding: dogs bark differently in various contexts, and we can tell the difference. A 2004 study by Sophia Yin and Brenda McCowan in *Animal Behaviour* reported that "disturbance barks" (emitted in response to a stranger ringing the doorbell) sound different from "isolation barks" (when a dog is separated from an owner) and barks emitted during play. In each context, the acoustics differ: whereas disturbance barks are "relatively low-pitched, harsh barks with little variation in pitch or loudness," isolation barks are "higher pitched, more tonal and more frequency modulated than the disturbance barks," and play barks are "similar to the isolation barks except that they usually occurred in clusters rather than singly."

Instead of seeing barks as meaningless noise, pay attention. Banjo might be yipping because he is alone, or he may have noticed that someone uninvited is climbing in through your second-floor window.

Dog barks are full of information, but what about growls? Anna Taylor, now at the Queen's University (Ontario) Bader International Study Center in England, found that, unlike barks, many acoustic properties of growls in a play and aggressive context are alike. But aggressive growls were longer than play growls, and play growls had a shorter pause between growls. Although growls from different contexts can sound similar to human ears, Tamás Faragó and his colleagues at the Family Dog Project at Eötvös Loránd University in Budapest found that growls carry considerable meaning in dog-dog communication.

In a 2010 study published in *Animal Behaviour,* dogs were placed in a room with a bone; as they approached the bone, researchers played a recording of one of three different types of growls. Dogs responded to the "this is my food" growl by backing away from the bone and, for the most part, ignored the "go away stranger" and the play growls because those sounds were not relevant to the bone. All growls are not the same, and dogs know it.

Even though not all growls are associated with aggression, an aggressive growl should not be ignored. If you come across a situation where growling could be a sign of aggression, keep your cool, though. Jolanta Benal, author of the 2011 *The Dog Trainer's Guide to a Happy, Well-Behaved Pet (Quick and Dirty Tips),* reminds: if you punish a dog for growling, you are essentially punishing it for giving a warning. Growling is a form of communication related to emotional or inner states in a particular context. If you want to decrease it, think about what is prompting it. The growling itself is not a problem.

Beware the Fear

KNOWING WHEN A DOG is happy is easy, but spotting fear is a lot harder, as Michele Wan, a certified applied animal behaviorist, and her colleagues showed in research examining whether people's perceptions of dogs' emotions vary according to experience. In the study, published in 2012 in *PLOS ONE,* volunteers—who were grouped as having little or no experience with dogs, having lived with a dog at some point, or working with dogs for more or less than 10 years—watched short video clips of dogs. Volunteers were asked to describe the dogs' emotional state and noted which body parts tipped them off. Because the videos had no sound, participants had to rely on behavior to label a dog as, say, fearful or happy. These videos were not just any videos. They had been prescreened by dog-behavior experts whose schooling or professional experience had trained them to make science-based assessments of animal behavior.

Happy dogs proved easiest to identify. Even people with little dog experience could watch a dog frolicking in the snow or rolling joyfully on its back and describe that dog as happy.

But fear was different. Study participants who were dog professionals did a better job identifying fear compared with both dog owners and people with little dog experience. "It did not matter whether the dog professionals were relative newcomers to the field, had worked with dogs for less than 10 years, or were longtime professionals with 10 or more years of experience," Wan adds. "They had the same proficiency in identifying fear."

One reason that the dog professionals did so much better could be that they looked at more dog body parts for clues, such as the eyes, ears, mouth and tongue, whereas nonprofessionals looked at fewer body parts and were less likely to tune into dogs' facial features.

Fortunately, you can learn how to notice and interpret subtle canine behaviors. Indeed, even if you live with the most happy-go-lucky dog on the planet, fear should still be on your radar, especially if your dog ever interacts with other dogs. Recognizing fear in another dog can help you know to give that dog space; the owner can take it from there.

What does fear look like? It can include a wide variety of body parts and postures. Wan and her colleagues explain that "fearful dogs are said to reduce their body size—crouching into a low posture, flattening their ears and holding their tails in a low position. Shaking, yawning, salivation, freezing, panting, paw lifting and vocalizing are examples of other behaviors that have been associated with fear in dogs."

It is possible to help dogs become less fearful. Noticing fear and related behaviors is the first step; identifying and modifying an animal's perception of fear-inducing stimuli is just as important. Picture a dog that is afraid of new people coming to the home, everyone from the postal delivery worker to your best friend. But now, when anyone comes to the home, the dog gets pieces of its most favorite food. Through counterconditioning, visitors gradually assume a new meaning as the dog associates people coming over with a good thing, in this case yummy food. As the dog's emotions shift, so, too, does its behavior—fearful postures fade away to reveal a dog anticipating something good, a dog essentially saying, "OMG!! A NEW PERSON IS HERE!! YES!!" A happy dog is born.

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When Animals Mourn

Mounting evidence from species as diverse as cats, dogs, giraffes and dolphins indicates that humans are not unique in grieving over the loss of loved ones

By Barbara J. King

ON A RESEARCH VESSEL IN THE WATERS off Greece's Amvrakikos Gulf, Joan Gonzalvo watched a female bottlenose dolphin in obvious distress. Over and over again, the dolphin pushed a newborn calf, almost certainly her own, away from the observers' boat and against the current with her snout and pectoral fins. It was as if she wanted to nudge her baby into motion—but to no avail. The baby was dead. Floating under direct sunlight on a hot day, its body quickly began to decay; occasionally the mother removed pieces of dead skin and loose tissue from the corpse.

When the female dolphin continued to behave in this way into a second day, Gonzalvo and his colleagues on the boat grew concerned: in addition to fussing with the calf, she was not eating normally, behavior that could be risky for her health, given dolphins' high metabolism. Three other dolphins from the Amvrakikos population of about 150 approached the pair, but none disrupted the mother's behavior or followed suit.

As he watched the event unfold in 2007, Gonzalvo, a marine biologist at the Tethys Research Institute in Milan, Italy, decided he would not collect the infant's body to perform a necropsy, as he would usually have done for research purposes. "What prompted me not to interfere was respect," he told me in 2013. "We were privileged to be able to witness such clear evidence of the mother-calf bond in bottlenose dolphins, a species that I have been studying for over a decade. I was more interested in observing that natural behavior than interrupting it by abruptly interfering and disturbing a mother who was already in obvious distress. I would define what I saw as mourning."

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Was the dolphin mother truly grieving for her dead calf? A decade ago I would have said no. As a biological anthropologist who studies animal cognition and emotion, I would have recognized the poignancy of the mother's behavior but resisted interpreting it as mourning. Like most animal behaviorists, I was trained to describe such reactions in neutral terms such as "altered behavior in response to another's death." After all, the mother might have become agitated only because the strange, inert status of her calf puzzled her. Tradition dictates that it is soft-hearted and unscientific to project human emotions such as grief onto other animals.

I think Gonzalvo was correct in his judgment that the mother dolphin was mourning. Indeed, in 2016, Melissa Reggente of the University of Milano-Bicocca and her colleagues published a stunning report that described 14 responses to death in seven species of whales and dolphins, including clear evidence of mourning. In the Red Sea near Egypt, for instance, an adult bottlenose dolphin repeatedly touched the body of a juvenile dolphin and pushed it in the water. Taken together, the new examples provide a clear window on grieving in cetacean cultures. In the past few years, in fact, a critical mass of new observations of animal responses to death has bubbled to the surface, leading me to a startling conclusion: cetaceans, great apes, elephants, and a host of other species ranging from farm animals to domestic pets may, depending on circumstances and their own individual personalities, grieve when a relative or close friend dies. That such a broad range of species—including some quite distantly related to humans—lament the passing of loved ones hints that the roots of our own capacity for grief run very deep indeed.

DEFINING GRIEF

SINCE CHARLES DARWIN'S DAY, two centuries ago, scientists have debated hotly whether some animals display emotions beyond those associated with parental care or other aspects of survival and reproduction. Darwin thought that, given the evolutionary connection between humans and other animals, many emotions must be similar across species. He granted to monkeys, for instance, grief and jealousy, as well as pleasure and vexation. But the attribution of emotions such as these to animals fell increasingly out of mainstream scientific favor. By the early 20th century the behaviorist paradigm held sway, with its insistence that only observable behavior of animals, not their interior lives, could be studied with rigor. Gradually the scientific embrace of animal emotion has revived, thanks originally in part to anecdotes from long-term field studies on large-brained mammals. From Tanzania, Jane Goodall recounted in heart-wrenching detail young chimpanzee Flint's decline and death from grief only weeks after the death of his mother, Flo. From Kenya, Cynthia Moss reported that elephants attend to dying comrades and stroke the bones of deceased relatives. Field biologists and anthropologists began to ask questions about whether, and how, animals mourn.

To study and understand grief among animals, scientists need a definition that distinguishes it from other emotions. Whereas "animal response to death" embraces any behavior by an individual following the death of a companion animal, researchers may strongly suspect grief only when certain conditions are met. First, two (or more) animals choose to spend time together beyond survival-oriented behaviors such as foraging or mating. Second, when one animal dies, the survivor alters his or her normal behavioral routine—perhaps reducing the amount of time devoted to eating or sleeping, adopting a body posture or facial expression indicative of depression or agitation, or generally failing to thrive. For his part, Darwin conflated grief with sadness. But the two differ, primarily in intensity: the grieving animal is more acutely distressed, possibly for a more prolonged period.

This two-part definition is imperfect. For one thing, scientists lack a metric for evaluating exactly what counts as "more acutely distressed." Should the criteria for grief differ according to species? Might grief in other animals assume forms that are difficult for humans to recognize as mourning? Data are not yet available on these questions. Further, mothers or other caretakers that constantly provide food or protection to infants that subsequently die cannot be said to have met the first criterion (going beyond survival-oriented behaviors), yet they remain among the strongest candidates for suffering survivor's grief.

Future studies of animal mourning will help refine this definition. For now, it furthers our critical assessment of responses made by animals when others around them die. For instance, baboon and chimpanzee mothers in wild African populations sometimes carry the corpse of their dead babies for days, weeks or even months—a behavior that on the surface of things might look like grief. But they may not exhibit any significant outward indicator of agitation or distress. When the animals carry on with their routine behaviors, such as mating, their behavior does not meet the criteria for mourning.

A MENAGERIE OF MOURNERS

A WIDE RANGE of species do exhibit behaviors that fit the two-part definition of grief, however, elephants among them. A particularly compelling example of elephant mourning comes from Iain Douglas-Hamilton of Save the Elephants and his team at Kenya's Samburu National Reserve, who in 2003 tracked elephants' responses to the dying matriarch called Eleanor. When Eleanor collapsed, a matriarch named Grace from another elephant family immediately came to her aid, using her tusks to support Eleanor back onto her feet. When Eleanor fell again, Grace stayed with her, pushing on her body, for at least an hour, even though her own family moved on. Then Eleanor died. During the course of the week that followed, females from five elephant families, including Eleanor's own, showed keen interest in the body. Some individuals appeared upset, pulling at and nudging the body with trunk and feet or rocking back and forth while standing over it. Based on the females' reactions (at no point during this

IN BRIEF

Animal behaviorists have traditionally shied away from attributing human emotions, such as grief, to responses by animals.

But a growing body of evidence indicates that species ranging from dogs to dolphins mourn the passing of relatives and close companions.

These observations suggest that although the ways in which we mourn may be uniquely human, our capacity for grief has deep evolutionary roots.

PRECEDING PAGES: TIM FLACH *Getty Images*

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DOLPHIN MOTHER CARRIES the body of her dead calf on her dorsal fin in the waters off Dana Point, Calif.

period did a bull elephant visit the carcass), Douglas-Hamilton concluded that elephants show a so-called generalized response to dying and death—grieving not only for the loss of close kin but for individuals in other families.

Wild cetaceans also seem to exhibit a generalized grief response. In 2001 in the Canary Islands, Fabian Ritter of Mammal Encounters Education Research observed a rough-toothed dolphin mother pushing and retrieving her dead calf's body in much the same way that the Amvrakikos dolphin mother later did with her baby's corpse. She was not alone: two adult escorts swam synchronously with her at certain periods, and at other times a group of at least 15 dolphins altered their pace of travel to include the mother and dead baby. The mother's persistence was remarkable, and when on the fifth day it began to wane, the escorts joined in and supported the infant on their own backs.

Giraffes, too, appear to grieve. In 2010 at the Soysambu Conservancy in Kenya, a female Rothschild's giraffe gave birth to a baby with a deformed foot. The baby walked less and remained more stationary than most calves. During the youngster's four weeks of life, wildlife biologist Zoe Muller of the Rothschild's Giraffe Project, based in Kenya, never saw the mother more than 20 meters away. Although individuals in a giraffe herd often synchronize their activities, foraging together, for example, the mother deviated from this pattern, preferring to stay close to the baby. Like the dolphin mother in the Amvrakikos Gulf, she may have risked her own health in doing so—though in this case for a living offspring.

One day Muller discovered the herd engaged in highly atypical behavior. Seventeen females, including the calf's mother, were vigilant and restless as they stared into a patch of bush. The calf had died in that spot about an hour before. All 17 females showed keen interest in the body that morning, approaching and then retreating from it. By the afternoon 23 females and four juveniles were involved, and some nudged the carcass with their muzzles. That evening 15 adult females clustered closely around the body—more closely than they had been during the day.

Throughout the following day numerous adult giraffes attended the infant's body. Some adult males approached for the first time, although they showed no interest in the carcass, instead focusing on foraging or inspecting the reproductive status of the females. On day three Muller spotted the mother giraffe alone under a tree about 50 meters from where the calf had died. The body itself, however, was no longer in its resting spot. Following a search, Muller located it, half-devoured, in the spot under the tree where the mother had been earlier. By the next day the body was gone, taken by hyenas.

Giraffes are highly social animals. After caching a newborn out of sight for about the first four weeks of life, the mothers sometimes engage in a crèche system in which one looks after the infants while the others forage. Muller does not use the word "grief" or "mourning" in describing the incident she witnessed. Yet this case is especially instructive. Not only the mother's behavior but also that of many of the females in her herd changed significantly in the wake of the infant's death. Although it is impossible to rule out an alternative explanation, the fact that the females had mounted a protective response against predators taking the baby makes it overwhelmingly likely that grief was involved.

Detailed observations of wild populations of animals, such as the ones Muller reported, are still relatively rare, for several reasons. Scientists may not be at the right place at the right time to observe post-death responses by survivors. And even when they are present, no remarkable grief behaviors may ensue. Especially at this early stage of research into animal grief, observations from sanctuaries, zoos and even

COURTESY OF CAPTAIN DAVE'S DOLPHIN AND WHALE WATCHING SAFARI, DANA POINT, CALIF.

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FEMALE GORILLA CLUTCHES her dead baby in a zoo in Münster, Germany. Although such behavior is not sufficient to demonstrate mourning, mothers that lose infants are among the strongest candidates for experiencing survivor's grief.

our own homes may supply needed clues.

I cannot imagine describing the behavior of Willa the Siamese cat without invoking the word "grief." For 14 years Willa lived with her sister, Carson, at the home of Karen and Ron Flowe in Virginia. The feline siblings groomed each other, lazed together in favorite parts of the house and slept with their bodies entwined. If Carson was taken from the house to visit the vet, Willa acted mildly agitated until she reunited with her sister. In 2011 Carson's chronic medical issues worsened, and the Flowes took her again to the vet, where she died in her sleep. At first, Willa acted as she did when her sister was away for a brief period. Within two or three days, though, she began to utter an unearthly sound, a sort of wail, and to search the spots she and Carson had favored together. Even when this startling behavior faded, Willa remained lethargic for months.

The loyalty of dogs to their human companions is legendary, and so may be their grief. Visitors to Tokyo sometimes make a pilgrimage to the Shibuya train station to view a statue of an Akita named Hachikō, who waited daily for more than a decade for his human friend Hidesaburō Ueno to step off a train. Ueno, a professor who had died suddenly at his university office, would never again walk home with Hachi (as the dog was nicknamed), but the dog maintained a hopeful vigil until his own death. This profound loyalty is also found in dog-dog friendships. The ASPCA's Companion Animal Mourning Project reports that two thirds of dogs show behavioral changes indicative of emotional upset, lasting up to six months, when another dog in the same household dies.

These statistics reflect my family's experience. My cousin Connie Hoskinson's silky terrier, Sydney, grieved twice over: for Connie's husband, George, when he died and later when her second dog, Angel, adopted when Sydney was 13 years old, suffered a sudden fatal heart attack. Without his canine friend—with whom he had slept and for whom he searched the house for weeks—Sydney ate less, lost weight and before long died in his sleep.

THE SORROW CONTINUUM

IT IS LOGICAL to think that long-lived species whose members partner most closely with others in tight-knit pairs, family groups or communities may more readily mourn the deaths of loved ones than other species do. But researchers do not yet know enough about animal grief to make such a claim. We need to test this hypothesis by systematically comparing responses to death in a variety of animal social systems, from gregarious ones to those in which animals come together only seasonally for food or mating.

Still, species-level differences in grieving will not be the whole story, because variation in the immediate social contexts and personalities of individual survivors will complicate matters. For instance, whereas the practice of allowing a survivor to view the body sometimes seems to prevent or reduce a period of distressed searching and vocalizing by the surviving animal, other times it seems not to help at all—attesting to the degree of individual variation in death responses within species. Likewise, evidence for grief in

ALAMY

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wild monkeys that live in cohesive social units is surprisingly limited so far, whereas in more solitary species such as domestic cats, bonds may develop between two or more kin or friends such that grief responses rival those of much more social animals. Some instances of grief in wild monkeys are coming to light, though, including in South American marmosets, Sichuan snub-nosed monkeys, and Barbary macaques. In my book, *How Animals Grieve,* I recount examples from rabbits, horses and birds, as well as the other animals discussed here. In each species I find a grief continuum, with some individuals seeming indifferent to a companion's death and other individuals appearing distraught over such a loss.

Cognitive differences also play a role in animal grief. Just as there are different levels of empathy expressed by different species and even across individuals within a species, there must be varying levels of comprehension when animals grieve. Do some animals grasp death's finality or even have a mental concept of death? We simply don't know. No evidence suggests that any nonhuman animal anticipates death in the way we humans do, a capacity that underlies so much of our compelling literature, music, art and theater—and that causes our species a great deal of emotional suffering.

Indeed, the capacity to mourn may become quite costly for any animal in both physical and emotional terms, especially in the wild where alert high-energy behavior is needed for foraging, predator avoidance and mating. Why then did grief evolve in the first place? Perhaps the social withdrawal that often accompanies an animal's grief, if not taken too far, allows time for rest and thus an emotional recovery that in turn leads to greater success in forging a new close bond. Or, as John Archer writes in *The Nature of Grief,* it may be that "the costs involved in grief can be viewed as a trade-off with the overall benefits conferred by separation responses" seen when two individuals are keenly attached but forced apart from each other.

Under such circumstances, the missing partners may search for each other and thereby reunite and live to see another day. What is adaptive, then, may not be grief itself but instead the strong positive emotions experienced before grief comes into the picture, shared between two or more living animals whose level of cooperation in nurturing or resource-acquisition tasks is enhanced by these feelings.

LOVE IN THE ANIMAL WORLD OFTEN ENTWINES WITH GRIEF IN AN ACUTE MUTUALITY.

THE PRICE OF LOVE

FROM THIS PERSPECTIVE, we may link grief with love, full stop. That is to say, grief results from love lost. Exploring emotions in a variety of species, ecologist and animal behaviorist Marc Bekoff of the University of Colorado Boulder embraces the idea that many animals feel "love" as well as "grief," even as he acknowledges that those concepts are hard to define precisely. We humans, he notes, do not fully understand love, but we do not deny its existence—or its power to shape our emotional responses.

In his book *Animals Matter,* Bekoff tells the story of a coyote called Mom whom he observed for several years during behavioral studies in Wyoming's Grand Teton National Park. At one point Mom began to make short journeys on her own away from her pack. Her offspring would rejoice when she returned: they licked Mom and rolled over exuberantly at her feet. Then Mom left for good. Some of the coyotes in her pack paced; others searched for her, setting off in the direction Mom had departed. "Her family missed her," Bekoff wrote. Discussing this with me, Bekoff attributed the family's response to its love for Mom. Generally, the potential for love is strong in species such as coyotes, wolves and many birds, he said, because male and female partners defend territories, raise their young together, and miss each other when they are apart.

Love in the animal world often entwines with grief in an acute mutuality. Perhaps even more than the degree of social cohesion within a species, it is love between individuals that predicts when grief will be expressed. Can there be any real doubt that Willa, a representative of a species (the domestic cat) not known for its social nature, loved her sister, Carson, or that as the sole surviving sister, she suffered grief in the wake of her loss?

In our own species, grief increasingly became expressed through rituals rich in symbolism. By around 100,000 years ago, our *Homo sapiens* ancestors decorated dead bodies in red ocher, a behavior interpreted by archaeologists to be a kind of symbolic (rather than functional) ornamentation. At a site in Russia called Sunghir, two children younger than 13 years, a boy and a girl, were buried 24,000 years ago, together with elaborate grave goods ranging from mammoth tusks to animals carved from ivory. Most astonishing were the thousands of ivory beads found in the pair's grave, probably sewn onto the clothing (long since disintegrated) in which the children were buried. A good portion of this ancient human community at Sunghir must have come together in preparing this funeral ritual—each bead alone took an hour or more to manufacture. Although it is risky to project modern emotions onto past populations, the examples of animal grief reviewed here strengthen an emotion-based interpretation of the archaeological evidence: our ancestors of many thousands of years ago mourned their lost children.

In our modern world, grief is no longer inevitably confined to kin, close social partners or immediate members of one's own community. Public commemoratives at the Peace Memorial Park in Hiroshima; the genocide memorial center in Kigali, Rwanda; the Foundation Memorial to the Murdered Jews of Europe in Berlin; the site of the Twin Towers in Manhattan; or the Sandy Hook Elementary School in Newtown, Conn., all convey visibly the power of agonized global mourning. Our human capacity for sorrow at the deaths of strangers is built on an evolutionary substrate. Our own ways of mourning may be unique, but the human capacity to grieve deeply is something we share with other animals. SA

Barbara J. King is a professor of anthropology at the College of William and Mary. Her studies of monkeys and apes have led her to examine emotion and intelligence in a wide range of animal species.

MORE TO EXPLORE

How Animals Grieve. Barbara J. King. University of Chicago Press, 2013.

Mind Your Moods, Cat Owners. Barbara J. King. NPR. January 22, 2015. www.npr.org/sections/13.7/2015/01/22/379008858/mind-your-moods-cat-owners

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BABY GORILLA Bokito is held by her mother, Aya, at Rotterdam Zoo in the Netherlands.

SECRET LIVES OF ANIMALS

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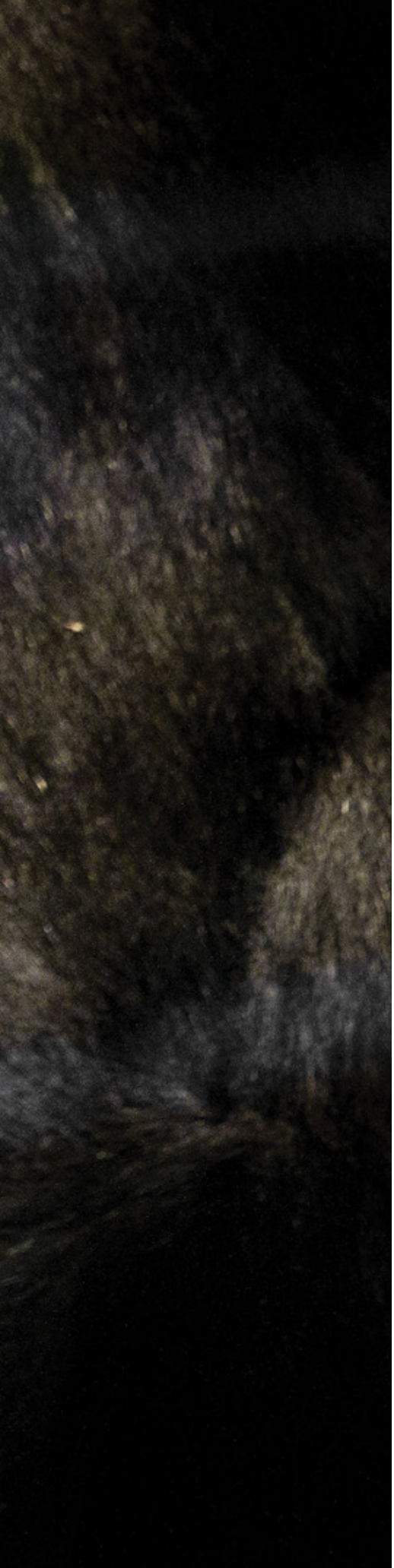

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DO ANIMALS KNOW WHERE BABIES COME FROM

Nonhuman species can seem to comprehend procreation, but even apes lack the cognitive traits to truly understand

By Holly Dunsworth

IN BRIEF

Animals often behave as though they know how babies are made.
Scientists have not studied this issue directly. But observations of how animals reason, communicate and plan imply that they lack the cognitive abilities needed to comprehend that sex produces offspring.
If our great ape cousins understood the birds and the bees, they would probably behave more like humans.

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YOU MAY KNOW KOKO AS A HUGE, HAPPY, CAPTIVE GORILLA WHO USES some sign language. She is 45 years old now. She lives in California. She likes kittens. She even understands the birds and the bees and can help plan her parenthood—or at least that's what a popular YouTube video would have us believe. In the video, Koko's caretaker, Francine "Penny" Patterson, presents the gorilla, who is too old to give birth herself, with a notepad outlining four scenarios by which she could become a mother.

A group of gorillas—one adult male, two adult females and a baby—could come live with Koko and her adult male companion, Ndume, Patterson tells Koko. Alternatively, a newborn and one or two older babies could join them; in a third scenario, just a single infant could be added. The fourth option, she explains, is that two adult females could be brought in to make babies with Ndume for Koko. Patterson hands the list to Koko, who stops scratching her chest and appears to contemplate her decision. With her right index finger, Koko taps at the last option on the notepad. "Very good idea because it would make Koko happy and it would make Ndume happy," the caretaker tells the gorilla.

So there we have it: Koko must know how babies are made. Why else would she choose baby makers over an actual baby?

It is popularly assumed that animals know all about where babies come from. In Koko's species, the sexually mature silverback males jealously guard so-called harems of females against other males. And victorious challengers often kill the infants sired by the defeated silverback before settling down to make their own. Furthermore, the gorillas avoid inbreeding between close kin by having individuals that reach reproductive age leave their family to go find a new one.

Gorillas hardly hold a monopoly on strategic sexual and parenting behaviors. Hens eject undesirable sperm before it fertilizes their eggs. Baboon dads step into the fray when their kids need social and political support. Some female chimpanzees holler when copulating with alpha males but not low-ranking ones—a means of advertising their attractiveness to other influential consorts. Everywhere we humans look, creatures are behaving as if they understand exactly what sex accomplishes, how they are related to potential mates as well as offspring, and how crucial it is to continue their line—with winning genes to boot. We love to narrate observations of animal sex and parenting with language that implies common ground between them and us. But do other species actually know that it is sexual intercourse that produces babies? Does Koko?

ANIMAL MINDS

IN FACT, there is no literature on whether animals understand reproduction. Scientists' best chance of finding out what animals know about how the world works comes from research conducted by primatologist Daniel Povinelli of the University of Louisiana at Lafayette on what nonhuman primates (the animals most like us cognitively) could fathom about physics and other areas involving cause and effect. In his books *Folk Physics for Apes* and *World Without Weight,* Povinelli describes decades of experimental work aimed at understanding what apes know about gravity.

Some chimpanzees can be successfully trained to sort objects by the effort required to lift them. But when they are then instructed to sort objects from heavy to light without lifting them first, the chimps perform no better than by chance—evidence that their comprehension does not arise from actually thinking about weight. As Povinelli puts it, the chimps' ability stems from physical smarts, not cerebral smarts.

To comprehend unobservable phenomena such as gravity or impregnation, a creature has to be capable of abstract reasoning, the ability to mentally form representations of unseen underlying causes or forces. Humans use abstract reasoning to transfer knowledge from one situation to another, which allows us to solve problems we have never encountered before and to even invent new diversions for ourselves. Although animals such as chimpanzees are far cleverer than scientists have traditionally acknowledged, they do not appear to have this particular cognitive skill. I'm reminded of the time an astute sixth grader answered my question about "Why don't chimps play baseball?" not with their anatomical incompatibilities but with "Because you can't explain the rules to them."

Of course, just because researchers have yet to detect abstract reasoning in apes does not necessarily mean it is absent. Let us say for the sake of argument that apes do have this ability. In that case, individual apes would all still have to independently discover that sex leads to babies, or they would need to share this reproductive knowledge using some form of language. Which brings us to our next problem. Other species do not have the gift of gab.

Koko can, as a result of years of training, name hundreds of objects when prompted, but she does not engage in discussion. Without her ability to sign, you probably would not be tempted to describe Koko's native verbal communication skills as sophisticated. Gorillas grumble in the presence of large amounts of food, they grunt as they approach one another or separate from their young, they make copulatory grunts, and they chuckle when they play. Primatologists Alexander H. Harcourt and Kelly Stewart, both then at the University of California, Davis, have studied these vocalizations in mountain gorillas (which are fundamentally similar in lowland gorillas, Koko's kind) and found that they are no more complex than the threat displays gorillas make in the heat of the moment. Their utterances telegraph social status and potential near-future behavior of the vocalist, but that is all.

Indeed, limited verbal skills are the norm among wild primates. Vervet monkeys have what is perhaps the closest thing to human language, and it does not begin to measure up in its complexity. As Dorothy Cheney and Robert Seyfarth of the University of Pennsylvania have observed from their extensive studies of

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these animals in East Africa, the vervets make distinct predator alarm calls for "eagle," "snake" and "leopard." These buzzy shrieks or "words" are not learned like human words but are innate. Although the alarm calls are arbitrary, like our words, they are never used to gab about a snake they saw yesterday or to fear-monger about a leopard they may encounter tomorrow. Even if one argued convincingly that these calls are monkey words, it is difficult to get from that rudimentary "language" to one in which the speaker can explain, "When we have sex, that's what starts a baby growing."

Moreover, there is no evidence to suggest that animals have a concept of time that would allow them to link a cause such as intercourse with such a delayed effect such as a baby and to plan accordingly. Orangutans, bonobos and chimpanzees have all been observed saving tools for future use. The most sinister is Santino, a chimp at a Swedish zoo, who hoards piles of rocks under a mop of hay for tossing at visitors when they least expect it. But present observations of so-called future planning in apes are hours or a few days at most—not nearly long enough to span their gestation period, which is nearly as long as that of humans.

If animals lack the abstract reasoning, language and future planning capabilities needed to intentionally procreate, then they must know what to do (have sex) even if they do not know why (that having sex is what allows them to produce offspring and perpetuate their species). Indeed, animals may carry out all kinds of seemingly complex behaviors without actually anticipating the outcomes. Cognitive scientist Sara Shettleworth of the University of Toronto points to the example of crows that drop walnuts on hard surfaces and thereby break the nuts open. Many observers assume that the crows consciously perform this behavior with the aim of obtaining food. But a more scientific approach to understanding the nut cracking, Shettleworth notes, is to assume the cause is "proximate": the bird's internal physiological state—hunger—is linked to the presence of walnuts and hard surfaces. That is, physiology that encourages conditioned food-procurement behavior based on past success is what causes a crow to fly above hard surfaces and drop nuts, not the crow's logic about how to best satiate its hunger.

Looking to proximate causes for animal behavior is a difficult concept for humans to accept. We assume that because we know why we do things, other animals doing something similar must also know, and we anthropomorphize their behavior. But that kind of reasoning lacks the rigor needed to truly understand animal cognition.

It is more logical to explain gorilla behavior, and indeed most of the things that animals do, without attributing to them any of our powers of imagination, especially where baby making and biological paternity are concerned. Consider the silverback who kills his new consort's offspring by another male. Infanticidal silverbacks can get more of their genes into future generations of gorillas than noninfanticidal ones. So if there is any biological basis for this complex behavior or for learning it, or both, it is passed on to their sons, who may repeat their behavior, and to their daughters, who may produce sons that exhibit it. These silverbacks must display less aggression around their kin and vice versa around non-kin, and this selectivity could be aided by familiarity over time. By the time the new silverback sires infants of his own, he has lost the urge to kill them, maybe because of behavior-influencing hormones that are communicating between his body, the babies and their mothers. No aspect of this phenomenon requires any reproductive or paternity knowledge on their part.

IF THEY ONLY KNEW

IF WE COULD somehow teach our great ape cousins that sex produces babies, then we might expect their behavior in the wild to change dramatically. Males and females that wanted offspring might start collecting semen and manually inserting it. Males might also stick around longer after coitus, potentially until birth, and then remain with the baby and mother until the youngster is old enough to live independently. Females might become more competitive for mating opportunities with males they prefer. If forced to mate against their will, they might even attempt to abort the pregnancy. Females who wanted to avoid pregnancy might hide themselves away during their estrous period, when they are fertile and attract the most male attention.

Knowing where babies come from would lead to an understanding of how individuals are related, which would have its own behavioral consequences. Both males and females might begin to take an interest in the reproductive behavior of their mature offspring and perhaps start positioning their family in the society when offspring are still immature so as to help them eventually land an elite mate. They might even prevent youngsters from leaving the group at reproductive maturity so they could better influence their reproductive lives. Brothers and sisters, knowing they come from the same parents, might also form tighter and more enduring relationships than they are known to do in these species. Aware of their relationship to offspring that mate with individuals in other groups and produce babies of their own, apes would probably show decreased competition and violence between groups that might have normally been enemies but are now understood to be blood-affiliated.

In other words, if apes comprehended that sex leads to babies, they would act a lot more like people. Which brings us back to Koko. I didn't just watch that one film of Koko. I watched many others, and in so doing I noticed that Koko practices her signs and learns new ones by exposure to symbols on a notepad. It seems that each time a symbol is presented to her she taps it with her finger first, whether she can recall and perform the correct sign or not. Koko's motherhood choice, then, did nothing to demonstrate that she understood the question, let alone baby making.

No matter how passionate or nurturing it is, nothing about the sexual, social and parental behavior of animals requires knowledge of reproduction. In contrast, much about *Homo sapiens* behavior does. Somewhere along the line, our species developed cultures rich in beliefs about procreation, family and connectedness—beliefs that in many ways set us apart from our ape cousins and indeed every other creature on the planet. SA

Holly Dunsworth is an anthropologist at the University of Rhode Island. She studies ape and human evolution, particularly when it comes to reproduction. Dunsworth is active in evolution education and contributes to the science blog The Mermaid's Tale.

MORE TO EXPLORE

Are We Smart Enough to Know How Smart Animals Are? Frans de Waal. W. W. Norton, 2016.

Personalities on the Plate. Barbara J. King. University of Chicago Press, 2017.

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GIA

SECRET LIVES OF ANIMALS

Illustration by James Gurney

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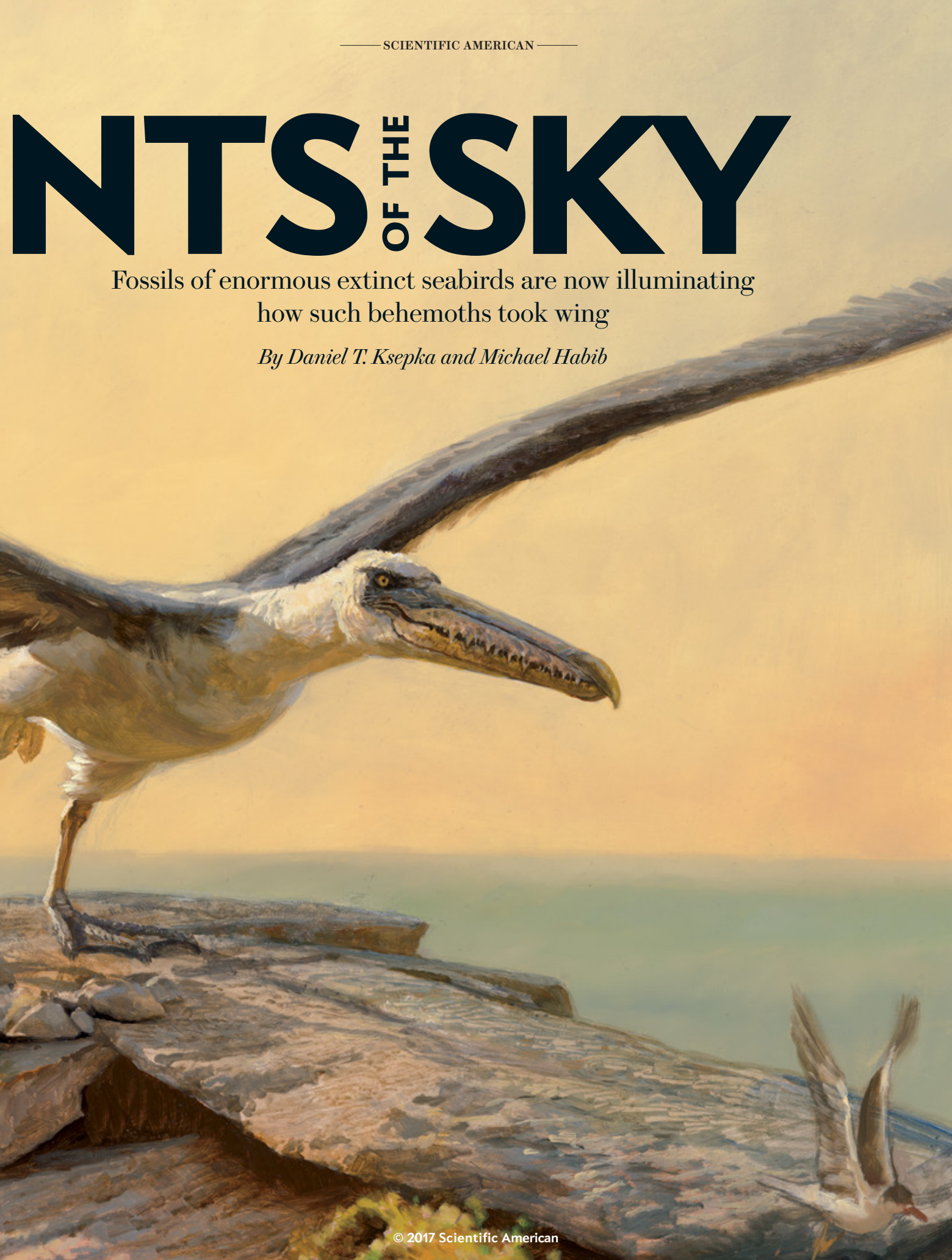
NTS OF THE SKY

Fossils of enormous extinct seabirds are now illuminating how such behemoths took wing

By Daniel T. Ksepka and Michael Habib



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IN ITS MODERN INCARNATION, SOUTH CAROLINA'S PICTURESQUE CHARLESTON HARBOR hosts a wide variety of marine birds—from the pelicans and cormorants that forage in its estuaries to the gulls and herons that breed and nest on its offshore islands and the songbirds that pass through en route to warmer climes for the winter months. Around 25 million years ago, however, dragons ruled the Carolina skies. These beasts were not the monsters of medieval folklore, of course, but rather evolution's closest facsimiles, fearsome in their own right: giant flying birds with wings longer than those of some light aircraft and beaks equipped with deadly, spearlike choppers.

The evidence for these terrifying creatures comes from fossils found at Charleston International Airport, appropriately enough. In 1983 a team led by paleontologist Al Sanders, then at the Charleston Museum, unearthed the bones and recognized that they belonged to a large bird. But the researchers had their hands full with other fossils, and the avian bones went into storage. Three decades would pass before an analysis carried out by one of us (Ksepka) revealed just how remarkable the forgotten animal was. Sanders and his colleagues had recovered the largest flying bird on record, a never before seen species belonging to an enigmatic group known as the pelagornithids. Ksepka named the creature *Pelagornis sandersi,* in honor of its discoverer.

For more than 150 years paleontologists have recognized that pelagornithids once patrolled the air. But with only a handful of fragmentary specimens available for study, little was known about how these animals flew, what their lives were like or why they evolved such extreme proportions. Recent analyses of the biggest of them all, *P. sandersi,* along with other studies of colossal avians carried out by the other of us (Habib), have filled in many gaps, helping to paint the most complete picture to date of these astonishing animals. The latest evidence indicates that pelagornithids rose to prominence in the aftermath of the asteroid impact that doomed the dinosaurs and their close relatives the flying pterosaurs and that they may have developed their impressive size as an adaptation to foraging over the open ocean. Whatever the driving force behind their gigantism, they were able to achieve sizes beyond the limits of what some researchers thought was possible for a flying bird.

ENIGMATIC BONES

THE STUDY OF PELAGORNITHIDS has a long, rich history. In 1857 French paleontologist Édouard Lartet described a very large wing bone of one of these birds, which he believed might have belonged to an ancient albatross. He dubbed it *Pelagornis miocaenus,* meaning simply "Miocene seabird." Although the name was uninspiring, the fossil was electrifying and mysterious. The wing bone, a humerus, measured nearly 0.6 meter (two feet) long, indicating that its owner had been a bird twice the size of some modern albatrosses—unthinkable in Lartet's day. Unfortunately, with just that piece of wing to go on, paleontologists had no real clue about what the rest of the animal looked like.

A hint that the owner of the huge bone was not a supersized albatross emerged more than a decade later, in 1873, when English anatomist Sir Richard Owen described the skull of another giant bird, which he assigned to a new species, *Odontopteryx toliapica*. His work made clear that the skull was so distinctive that it could not belong to any of the modern bird groups. Instead it represented a previously unrecognized group of huge extinct birds. The eventual discovery of more complete specimens revealed that Lartet's humerus belonged to this same group.

Additional discoveries came to light slowly over the next century, sometimes vanishing soon afterward. In 1910 one of the most complete pelagornithid skulls ever found was attributed to a new species, *Pseudodontornis longirostris.* The University of Königsberg in Germany had purchased the skull from a Brazilian sailor. But during World War II, Allied bombing devastated Königsberg, which was annexed by the Soviet Union and re-

IN BRIEF

Paleontologists have long known that strange birds called pelagornithids once ruled the skies.

Some pelagornithid species evolved sizes that far exceeded those of the largest modern-day flying birds.

The recent unveiling of a new species in this group—the biggest bird known to have ever taken to the air—has helped scientists figure out how these astounding animals flew and why they evolved giant proportions.

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LARGELY COMPLETE SKULL of extinct bird *Pelagornis sandersi*, seen here from various angles, exhibits the distinctive "false teeth" of the pelagornithid family of birds. The teeth are hollow projections formed from bone and would have helped the predatory *P. sandersi* grasp prey.

COURTESY OF CHARLESTON MUSEUM

named Kaliningrad at the end of the war. Today the fossil's whereabouts are unknown; no one is sure if it was destroyed in the conflict, stolen or removed to another location.

In the decades that followed, fossil hunters discovered more pelagornithid species, including *Pelagornis orri* from California and *Pelagornis chilensis* from Chile. Whereas most of the earliest finds were scrappy, partial skeletons from these new species allowed scientists to begin piecing together a more detailed understanding of how these animals were built and what kinds of activities they were adapted to perform.

The emerging picture defied imagination. Foremost on the long list of unusual features of pelagornithids are the serried ranks of toothlike structures that line their upper and lower jaws. Birds lost the ability to form teeth more than 65 million years ago. But pelagornithids evolved a work-around. Unlike true teeth, which are composed of enamel and calcified tissue known as dentine and are set in sockets, the so-called pseudoteeth of pelagornithids were hollow projections formed directly from bone. These pseudoteeth were arranged in orderly, repeating sets of size classes in the best-known species. A pair of short, thin, needlelike pseudoteeth flanked each of the medium-sized projections, and a pair of these three-tooth packages in turn flanked the tallest, conelike pseudoteeth. In life, a thin layer of the same material that sheathes the beak of modern birds probably covered the bony teeth. The overall effect was that of a menacing grin rippling with spikes adapted to nabbing and holding onto prey.

Other weird traits further enhanced the hunting prowess of

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It's a Bird, It's a Plane

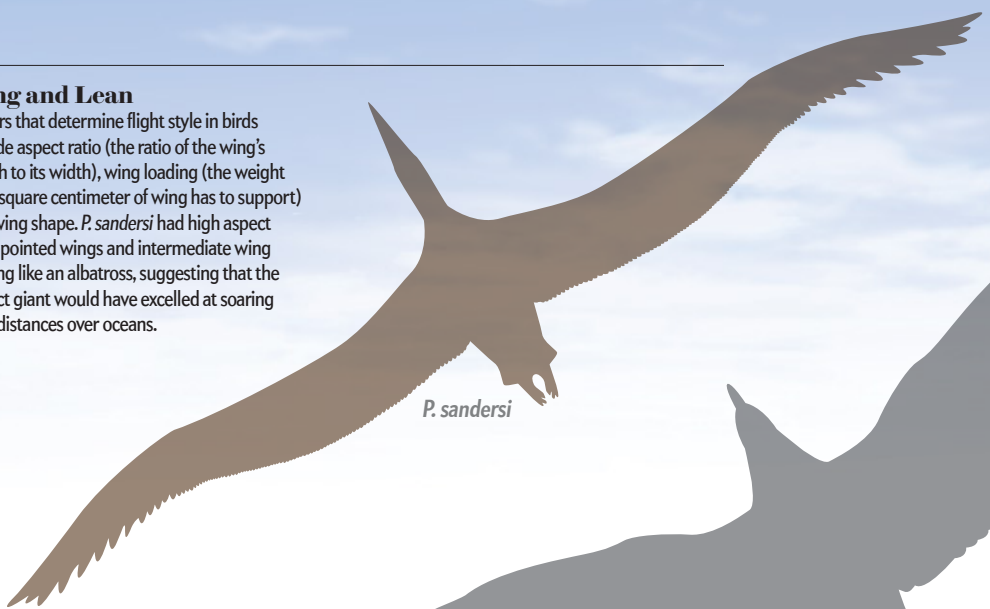
Recent analyses of the *P. sandersi* bones, which were discovered decades ago on airport grounds, showed that this creature is the biggest flying bird on record—more than twice the size of the modern record holder, the wandering albatross. In fact, *P. sandersi* is bigger than some experts had thought possible for a volant bird. But it possesses several key adaptations for air travel (*right*). Comparing this animal's proportions with those of living birds helped researchers to reconstruct its flight style (*below*).

Shoulder

The shoulder blade is incredibly small compared with the rest of the body, which suggests the muscles attaching to the wing from the back became highly reduced as the need for flapping flight diminished. In addition, the unusual, almost square shape of the end of the humerus prevented rotation at the shoulder joint, which hindered flapping but helped to stabilize the wing during gliding flight.

Long and Lean

Factors that determine flight style in birds include aspect ratio (the ratio of the wing's length to its width), wing loading (the weight each square centimeter of wing has to support) and wing shape. *P. sandersi* had high aspect ratio, pointed wings and intermediate wing loading like an albatross, suggesting that the extinct giant would have excelled at soaring long distances over oceans.



Argentavis

This extinct species, which previously held the title of largest known flying bird, is inferred to have had condor-like wings with low aspect ratio and slotted wing tips.

Illustrations by Raúl Martín (P. sandersi) and Daisy Chung (silhouettes)

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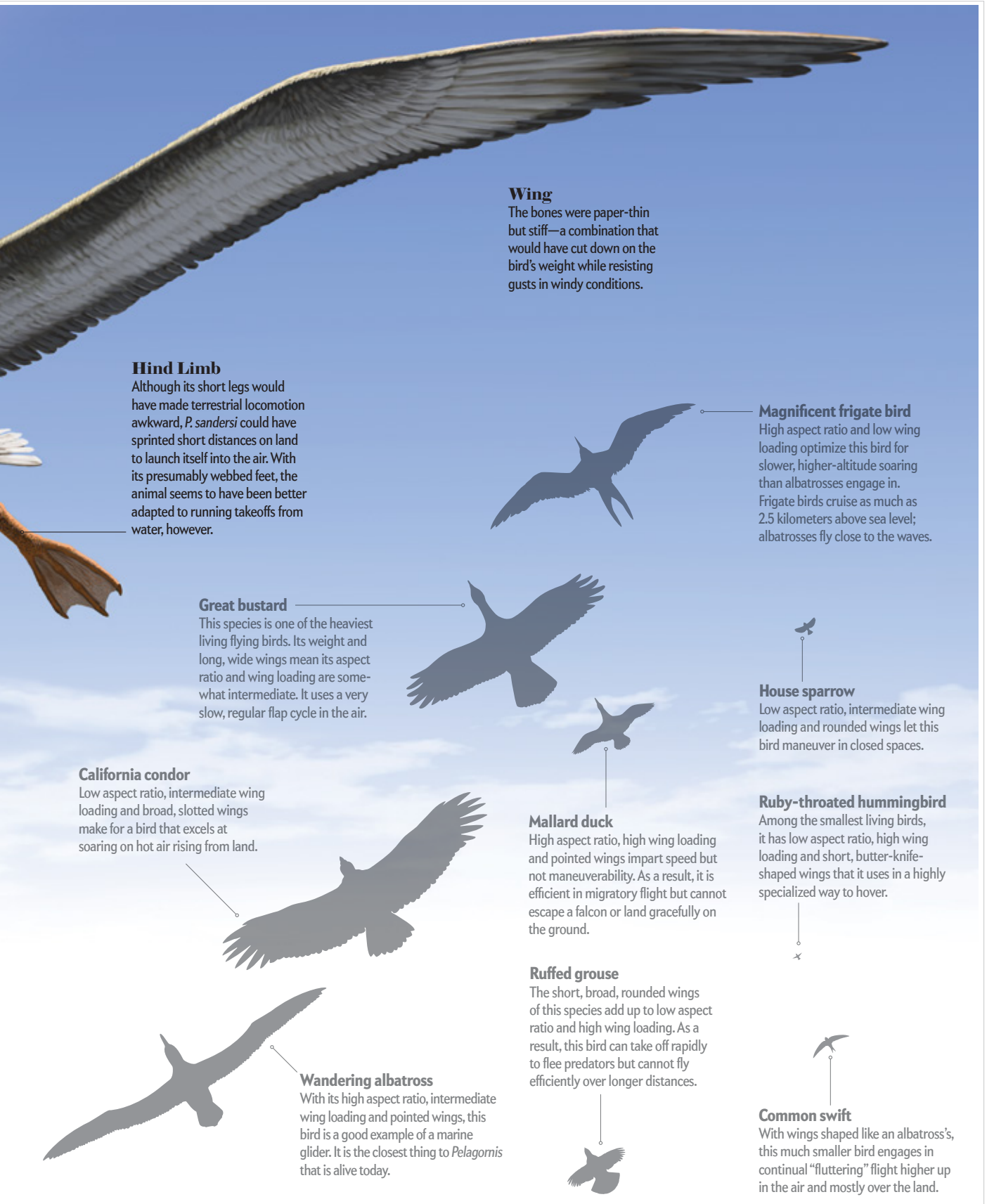

Wing
The bones were paper-thin but stiff—a combination that would have cut down on the bird's weight while resisting gusts in windy conditions.

Hind Limb
Although its short legs would have made terrestrial locomotion awkward, *P. sandersi* could have sprinted short distances on land to launch itself into the air. With its presumably webbed feet, the animal seems to have been better adapted to running takeoffs from water, however.

Magnificent frigate bird
High aspect ratio and low wing loading optimize this bird for slower, higher-altitude soaring than albatrosses engage in. Frigate birds cruise as much as 2.5 kilometers above sea level; albatrosses fly close to the waves.

Great bustard
This species is one of the heaviest living flying birds. Its weight and long, wide wings mean its aspect ratio and wing loading are somewhat intermediate. It uses a very slow, regular flap cycle in the air.

House sparrow
Low aspect ratio, intermediate wing loading and rounded wings let this bird maneuver in closed spaces.

California condor
Low aspect ratio, intermediate wing loading and broad, slotted wings make for a bird that excels at soaring on hot air rising from land.

Mallard duck
High aspect ratio, high wing loading and pointed wings impart speed but not maneuverability. As a result, it is efficient in migratory flight but cannot escape a falcon or land gracefully on the ground.

Ruby-throated hummingbird
Among the smallest living birds, it has low aspect ratio, high wing loading and short, butter-knife-shaped wings that it uses in a highly specialized way to hover.

Ruffed grouse
The short, broad, rounded wings of this species add up to low aspect ratio and high wing loading. As a result, this bird can take off rapidly to flee predators but cannot fly efficiently over longer distances.

Wandering albatross
With its high aspect ratio, intermediate wing loading and pointed wings, this bird is a good example of a marine glider. It is the closest thing to *Pelagornis* that is alive today.

Common swift
With wings shaped like an albatross's, this much smaller bird engages in continual "fluttering" flight higher up in the air and mostly over the land.

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pelagornithids. The skull of these birds was uniquely flexible. Its midpoint had a strong hinge that permitted bending at the spot where the braincase met the upper beak. Additionally, the lower jaw had a joint built into the midpoint of the left and right sides. Instead of solid bone, the jaw was held together at the "chin" by a flexible ligament. Together these traits would have enabled substantial bending of the jaws, perhaps to accommodate large prey.

Bones from below the head also distinguish pelagornithids from other avians. The wing bones of these birds are so flattened that some paleontologists actually arranged one of them, the humerus, upside down in past skeletal reconstructions. Although all flying birds have hollow bones, which make their skeletons structurally efficient, pelagornithids took that trend to extremes. All their wing elements exhibit exceptionally thin bone walls. This thinness means the birds retain the bone stiffness they need with a minimum of weight—critical for giant flying animals. But lightly built bones have a downside: an unexpected collision might spell doom because such bones are easier to fracture. A break in one of them would ground the bird, leaving it unable to feed.

IT SEEMED INCONCEIVABLE THAT FOSSILS OF SUCH ENORMOUS SIZE COULD EVEN BELONG TO A BIRD.

The leg bones are arguably the most normal part of pelagornithids, at least in terms of their shape. Yet they are almost comically small compared with the wing bones. Nevertheless, the hind limb bones had reinforced walls and a stout shape that would have made them relatively strong. Like many living seabirds, pelagornithids were probably somewhat awkward when it came to crossing large distances on land. But all they needed, presumably, was the ability to sprint effectively for short distances to initiate takeoff.

RECORD BREAKER

BY THE TIME *P. SANDERSI* was finally described in 2014, scientists had already established that the pelagornithids were highly unusual birds. But *P. sandersi* one-upped even that strange company. Its humerus alone measured nearly a meter (around three feet) in length—more than a third longer than Lartet's original pelagornithid humerus and even longer than the entire arm of an average person. It seemed inconceivable that fossils of such enormous size could even belong to a bird. Indeed, some research suggested a theoretical limit of 5.1 meters for wingspan in a marine soaring bird, beyond which an animal simply would be too heavy to remain aloft by flapping. Yet the limb bones found at the Charleston airport clearly represented an avian wing and leg, as indicated by their telltale wafer-thin walls, which needed careful treatment with chemical hardening agents to keep them from crumbling into shards. And there was no mistaking the accompanying skull, with its trademark pseudoteeth, for anything other than a pelagornithid.

The excellent preservation of these skeletal elements, combined with insights from other pelagornithid specimens, allows for a detailed reconstruction of *P. sandersi*. In life, the feathered wings of this bird would have measured an estimated 6.06 to 7.38 meters (20 to 24 feet) tip to tip—the largest wingspan of any bird on record, living or extinct, and more than double the average wingspan of the largest modern flying bird species, the wandering albatross. Extrapolating from the circumference of the weight-bearing leg bones, *P. sandersi* would have tipped the scales at somewhere between 21.9 and 40.1 kilograms (48 to 88 pounds)—the weight of a golden retriever. Though massive compared with modern fliers, the animal was dainty for its wingspan, thanks to its small body and ultralightweight skeleton.

Proceeding from those parameters, we have worked out how this magnificent creature and other giant pelagornithids flew. Estimating the locomotor capabilities of extinct animals is a tricky exercise, but researchers today have better tools than ever before to do so. Key observations from living birds, along with fundamental physical principles from aerodynamics, informed our proposed flight scenario.

Today's flying birds exhibit a wide variety of flying styles, such as the hummingbird's hovering and the seagull's slower flapping flight. Right away the incredibly long wings of *P. sandersi* and other pelagornithids suggested that their primary mode of flight was soaring, in which the wings do not flap to generate lift but instead are held outstretched to use energy from wind or rising air. Modern soaring birds have a few different ways of remaining aloft for long periods, though, and figuring out what strategy pelagornithids employed required deeper analysis.

Species such as condors and vultures possess broad wings relative to their body weight, which creates what is termed low wing loading—that is, each square centimeter of wing is required to support relatively fewer grams than would be needed in a bird of comparable mass but less expansive wings. The wings of these birds also have slotted tips, meaning that the feathers at the tip of the wing can spread apart, reducing drag. The combination of low wing loading and slotted wing tips enables these animals to surf currents formed by warm air as it wafts up from land. And it allows them to do so with relatively shorter wings than seabirds have, which comes in handy when navigating environments with obstacles such as cliffs and vegetation.

Frigate birds pursue a second type of soaring, traveling on thermals that form over ocean rather than land. They have more slender, tapered wings with pointed, rather than slotted, tips. They are also among the most lightly built of all birds and thus exhibit exceptionally low wing loading. These traits aid frigate birds in traveling long distances while cruising high up in the sky, ready to swoop down to capture prey near the sea surface.

At the other end of the marine soaring spectrum are the albatrosses, which also have very long, narrow wings with pointed tips. Albatrosses, however, are heavier relative to their wing area, which means they need strong, fast winds to power their flight. Albatrosses fly by harnessing the wind gradient above the waves. They fly into the slower wind near the surface of the water to gain altitude and then curve around to ride the stronger winds back down to sea level, endlessly looping to gain altitude and trade it for distance in a maneuver called dynamic soaring. In 2004 an albatross outfitted with a tracking device was clocked moving an average of 127 kilometers an hour for nine hours straight—the record sustained soaring speed for any living animal. It was riding winds from an Antarctic storm.

Improved knowledge of pelagornithids from spectacular specimens like that of *P. sandersi* suggests that these birds specialized in a form of soaring not seen among today's soaring

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birds. Their wings were narrow but still large in area thanks to their great length. In other words, evolution gave these birds the best of two worlds: their large overall size would have allowed them to use dynamic soaring when winds were strong, and with their large wing area and high aspect ratio, they would have also excelled at cruising over quiet oceans for thousands of kilometers at a time. The biggest pelagornithids would have been able to cover those distances relatively rapidly: we calculated that the speed of optimal efficiency for these giants would have been more than 40 kilometers an hour, putting them well ahead of the pace attained by world record holder of the 100-meter dash, Usain Bolt, who broke the ribbon at 9.58 seconds—equivalent to running 37.6 kilometers an hour. Moreover, *P. sandersi* could have maintained that pace with relatively little effort: after gaining 45 meters of altitude, the bird could glide for more than a kilometer without any flapping or assistance from winds.

Although *P. sandersi* probably spent most of its time on the wing, it would have to land occasionally (to nest, for example), which would also mean taking off again. The tiny legs of large pelagornithids originally led some researchers to question the ability of these large birds to launch effectively. But with the discovery of more complete behemoths, including *P. chilensis* and *P. sandersi,* it became apparent that the hind limbs were actually well proportioned to the relatively compact bodies of these giant birds. The first ever quantitative analysis of launch mechanics in giant pelagornithids, presented by Habib at a premiere international paleontology meeting, found that the short, stout hind limbs of *Pelagornis* were appropriately shaped and positioned for brief sprints, especially over water surfaces (the feet in *Pelagornis* were most likely webbed). The bones of the hind limbs were also sufficiently strong to support significant muscle mass, able to propel the modest-sized bodies (with their oversized wings) up to launch speeds. These leg traits would have made *P. sandersi* an excellent water launcher, even if it was probably relatively poor at walking over land.

A VACANT NICHE

THE DISCOVERY OF *P. SANDERSI*—a titan among what were already considered to be exceptionally large birds—raises the question of why giant size evolved in flying avians. Gigantism is not universally advantageous in biology. Big animals need more food than small ones, they may require larger areas for nesting and they tend to have smaller population sizes than modestly proportioned species. Yet despite those drawbacks, multiple successful lineages of giant fliers have evolved over the course of the earth's history. In fact, the lack of truly enormous fliers today is the exception to the rule: giant flying animals darkened the skies for most of the past 120 million years.

It turns out that large size has a considerable upside. For one, it improves the efficiency of long-distance flight because bigger fliers use less energy per unit distance covered than their small counterparts do. Larger animals can also capture (or steal) prey that smaller fliers cannot handle. Furthermore, large flying animals have limited predation risk—once airborne, a big flier is almost immune to attack from predators.

For millions of years the winged reptiles known as pterosaurs ruled the airspace over land and sea. Those living over the oceans probably fed on invertebrates and fish, and they had body plans well adapted to long-distance ocean voyages. They were very successful. But the same asteroid impact that extinguished the dinosaurs (apart from birds, which are living dinosaurs) also did in the pterosaurs. With their extinction, competition in several realms suddenly plummeted, and the ecological "niches" they had occupied opened up. One of these niches was that of the large, marine soarer.

Pelagornithids appear to have filled this role, debuting approximately 10 million years after the last pterosaurs. Their fossils come almost exclusively from sedimentary deposits in ocean environments, indicating that marine prey formed the mainstay of their diet. Because their pseudoteeth were not very strong compared with true teeth, some paleontologists speculate that soft-bodied animals such as squid and eels found near the ocean surface may have been the primary food source. Other, more ill-gotten morsels may also have been on the menu. Today large marine birds often bully other species into relinquishing their food, sometimes even harassing other birds in flight until they vomit up their prey, as the skua does. By far the largest birds in their ecosystems, pelagornithids may well have harangued smaller seabirds to rob them of meals. They also could have snatched chicks from their nest, a predation behavior practiced by modern giant petrels, skuas and even some pelicans.

Pelagornithids were not the only large birds to help fill the roles vacated by pterosaurs: another group of large flying birds, the teratorns, appeared about 23 million years ago and survived all the way up to the end of the Pleistocene epoch, 11,700 years ago. With their shorter, broader wings and heavier bodies, they probably flew and hunted more like condors.

After soaring over the seas for more than 50 million years, pelagornithids vanished completely roughly three million years ago during the Pliocene epoch. The root cause of their disappearance remains a mystery. The Pliocene witnessed profound changes in the oceans as the Panama land bridge closed, sundering a major connection between the Atlantic and the Pacific and radically altering currents. Yet it is hard to imagine even this event ending a lineage that had survived so many previous shifts in climate, ocean circulation and fauna.

Perhaps overspecialization played a role in the demise of pelagornithids. Early in the radiation of this group, several "small" species, which reached the size of modern albatrosses, evolved. Over time these diminutive forms died out, and for the last half of pelagornithid history only giant species remained. These behemoths may have relied more heavily on specialized feeding strategies and global wind currents than smaller marine birds did—and ultimately became victims of their own success. SA

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Michael Habib is an anatomist at the University of Southern California. He studies the biomechanics of extinct animals, including birds and pterosaurs.

MORE TO EXPLORE

Constraining the Air Giants: Limits on Size in Flying Animals as an Example of Constraint-Based Biomechanical Theories of Form. Michael Habib in *Biological Theory,* Vol. 8, No. 3, pages 245–252; September 2013.

Flight Performance of the Largest Volant Bird. Daniel T. Ksepka in *Proceedings of the National Academy of Sciences USA,* Vol. 111, No. 29, pages 10,624–10,629; July 22, 2014.

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THE NOSE TAKES A STARRING ROLE

The star-nosed mole has what is very likely the world's fastest and most fantastic nose

By Kenneth C. Catania

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THE RENOWNED PHYSICIST JOHN ARCHIBALD Wheeler once suggested, "In any field, find the strangest thing and then explore it." Certainly it is hard to imagine an animal much stranger than the star-nosed mole, a creature you might picture emerging from a flying saucer to greet a delegation of curious earthlings. Its nose is ringed by 22 fleshy appendages that are usually a blur of motion as the mole explores its environment. Add large clawed forelimbs, and you've got an irresistible biological mystery. How did this creature evolve? What is the star? How does it function, and what is it used for? These are some of the questions that I set out to answer about this unusual mammal. It turns out that the star-nosed mole has more than an interesting face; it also has a remarkably specialized brain that may help answer long-standing questions about the organization and evolution of the mammalian nervous system.

It may comfort you to know that star-nosed moles (*Condylura cristata*) are small animals, tipping the scales at a mere 50 grams, about twice the weight of a mouse. They live in shallow tunnels in wetlands across much of the northeastern U.S. and eastern Canada and hunt both underground and underwater. Like the other roughly 30 members of the mole family (*Talpidae*), the star-nosed mole is part of the mammalian order Insectivora, a group known for its high metabolism and voracious appetite. So the tiny star-nosed mole with its big appetite must locate enough prey to survive cold northern winters. It finds earthworms in soil, as other moles do, but in addition it has access to a host of small invertebrates and insect larvae found in the rich mud and leaves of its wetland habitat and in the ponds and streams where it swims along the murky bottom to root out prey. And seeking prey is where the star comes into play. The star is not part of the olfactory system—which governs smell—nor is it an extra hand used to gather food. Instead the star is a touch organ of unsurpassed sensitivity.

PINK STAR makes this mole's nose unmistakable. It also makes it one of the most sensitive touch organs observed in the animal kingdom—one that works uncannily like an eye.

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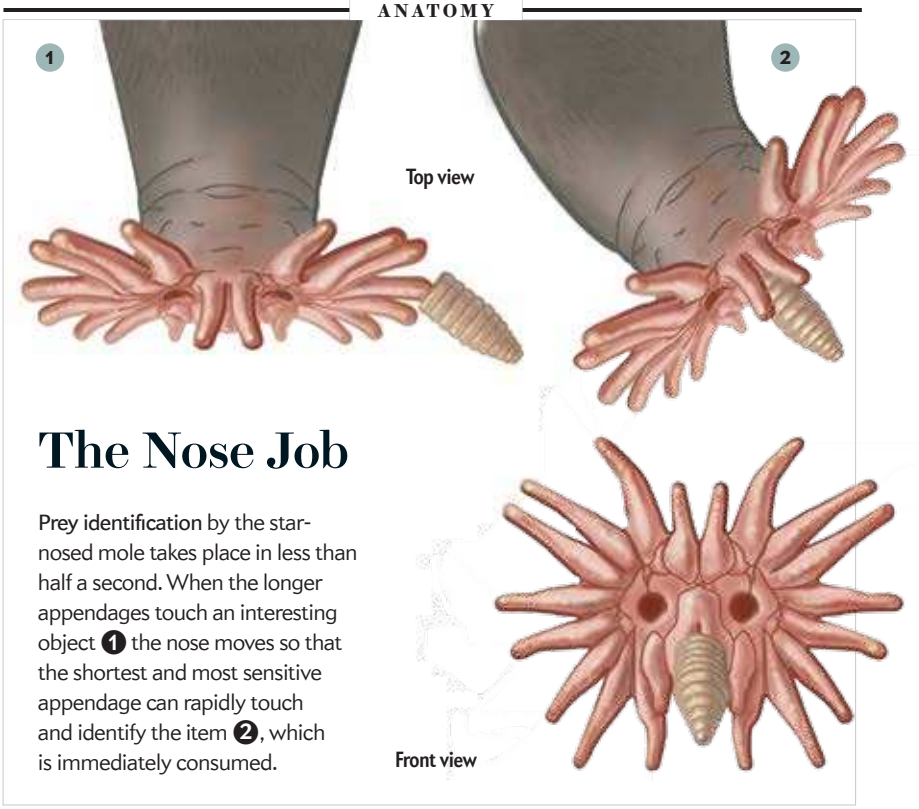
ANATOMY



The Nose Job

Prey identification by the star-nosed mole takes place in less than half a second. When the longer appendages touch an interesting object ❶ the nose moves so that the shortest and most sensitive appendage can rapidly touch and identify the item ❷, which is immediately consumed.

GETTING CLOSE TO THE STAR

WHEN I BEGAN to explore the anatomy of the star with a scanning electron microscope—an instrument that reveals the microscopic structure of the skin surface—I thought I would see touch receptors here and there in various places across the skin. Instead I was surprised to find that the star, like the retina in the human eye, is made up *entirely* of sensory organs. The surface of each of the 22 appendages that ring the nostrils is composed of an aggregation of microscopic protuberances, or papillae, called Eimer's organs. Each Eimer's organ, in turn, is made up of an array of neural structures, each of which signals different aspects of touch.

Three distinct sensory receptors accompany each Eimer's organ. At the very bottom of the organ is a single nerve ending that is encircled by many concentric rings, or lamellae, of tissue formed by a Schwann cell, a specialized support cell. This lamellated receptor transmits relatively simple information about vibrations or about when an individual organ first contacts an object. Above this receptor is another nerve fiber that makes contact with a specialized cell called a Merkel cell. Unlike the lamellated variety, the Merkel cell-neurite complex signals only the sustained depression of the skin. Both these receptors are commonly found in mammalian skin.

At the top of each Eimer's organ, however, lies a receptor unique to moles. A series of nerve endings forms a circular pattern of neural swellings in a hub-and-spoke arrangement just below the outer skin surface. Our recordings from the brains of star-nosed moles suggest that this latter sensory component provides the most significant aspect of touch perception: an index of the microscopic texture of various surfaces.

More than 25,000 Eimer's organs form the star, although it has a surface area of less than one square centimeter. Together these sensory organs are supplied by more than 100,000 nerve fibers that carry information to the central nervous system and eventually to the highest mammalian processing center, the neocortex. With this formidable array of receptors, the mole can make incredibly fast sensory discriminations as it prowls its haunts looking for prey.

The star moves so quickly that you can't see it with your naked eye. A high-speed camera revealed that the star touches 12 or more areas every second. Scanning its environment with a rapid series of touches, a star-nosed mole can find and eat five separate prey items, such as the pieces of earthworm we feed them in the laboratory, in a single second.

ACTING LIKE AN EYE

EVEN MORE SURPRISING than this astonishing speed is the manner in which the mole uses the star. The star functions like an eye. Try reading this sentence without moving your eyes, and you will soon appreciate that your visual system is divided into two distinct functional systems. At any given time only a small portion of a visual scene (about one degree) is analyzed with the high-resolution central area of your retina, the fovea. The much larger low-resolution area of your retina locates potentially important areas to analyze next. The characteristic rapid movements of the eyes that reposition the high-resolution fovea are called saccades.

Just as we scan a visual scene with our eyes, star-nosed moles constantly shift the star to scan tactile scenes as they travel through their tunnels, quickly exploring large areas with the Eimer's organs of all 22 appendages. But when they come

IN BRIEF

The star-nosed mole has 22 appendages on the front of its face that form a star. These appendages are sensory organs that enable the mole to feel around in underground tunnels for food at mind-boggling speed—a star-nosed mole can find and eat five separate prey items in a single second.

Three sections of the mole's neocortex respond to tactile stimulation, analyzing information from more than 100,000 nerve fibers. The neurons themselves form the shape of a star.

Many mammals have evolved high-resolution centers in the brain for visual, auditory and sensory input. In star-nosed mole embryos, the 11th appendage develops first, potentially spurring early development of corresponding regions of the brain.

PRECEDING PAGES: KENNETH C. CATANIA; THIS PAGE AND OPPOSITE PAGE: PORTIA SLOAN (*illustrations*)

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across an area of interest—such as potential food—they always shift the star so that a single pair of appendages can carry out more detailed investigations. In the same way humans have a fovea for sight, star-nosed moles have a fovea for touch. The mole's fovea consists of the bottom pair of short appendages, located above the mouth, each designated as the 11th appendage. Like the retinal fovea, this part of the star has the highest density of sensory nerve endings. Moreover, the rapid movements of the star that reposition this tactile fovea onto objects of interest are analogous to saccades in the visual system.

The analogy goes even further. In our visual system it is not only the movements of the eyes and the anatomy of the retina that revolve around the high-resolution fovea; human brains are specialized to process information predominantly from this part of the visual scene.

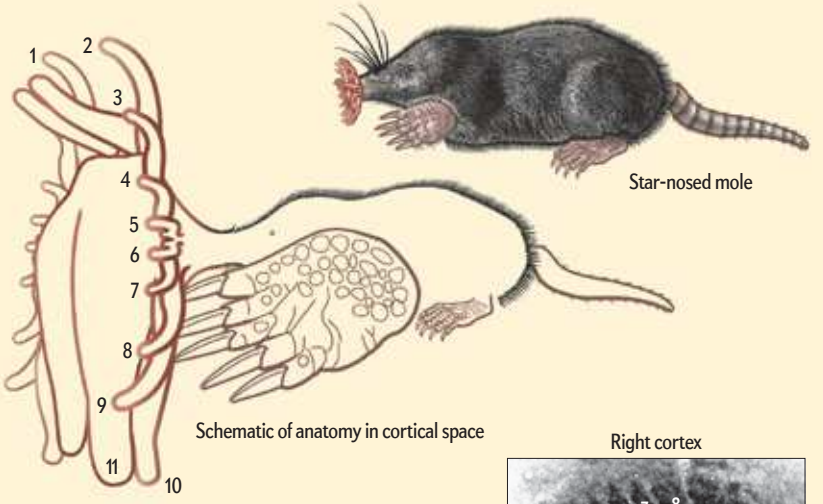
A characteristic feature of information processing in mammalian sensory systems is the topographic organization of information from sensory receptors. Visual areas contain maps of the retina, auditory areas provide maps of the cochlea (the receptors in the ear, which are maps of tones), and touch areas contain maps of the body's surface. Such mapping is perhaps nowhere better illustrated than in the somatosensory system of the star-nosed mole.

CHARTING TOUCH

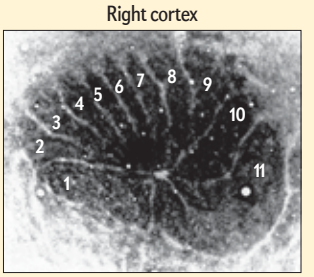
WORKING WITH my Vanderbilt University colleague Jon H. Kaas, I was able to explore the organization of the star-nosed mole's neocortex. By recording the activity from neurons that compose different cortical areas, we charted the neural representation of the star, showing where and how neurons in the cortex respond to tactile stimulation of the Eimer's organs. We identified three separate maps of the star where the responses of neurons reflect the anatomy of the nose on the opposite side of the face. (In all mammals, the left half of the body is represented predominantly in the right side of the cortex, and vice versa.) To our amazement, we also found that these maps are visible in sections of the brain that were stained for various cell markers—we could literally see a star pattern in the cortex.

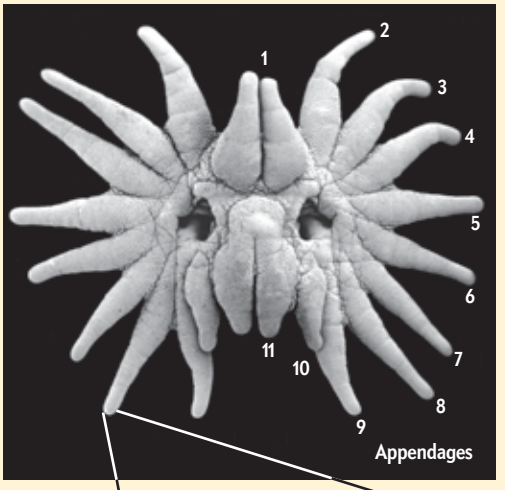
KENNETH C. CATANIA (*micrographs*)

How the Nose Knows

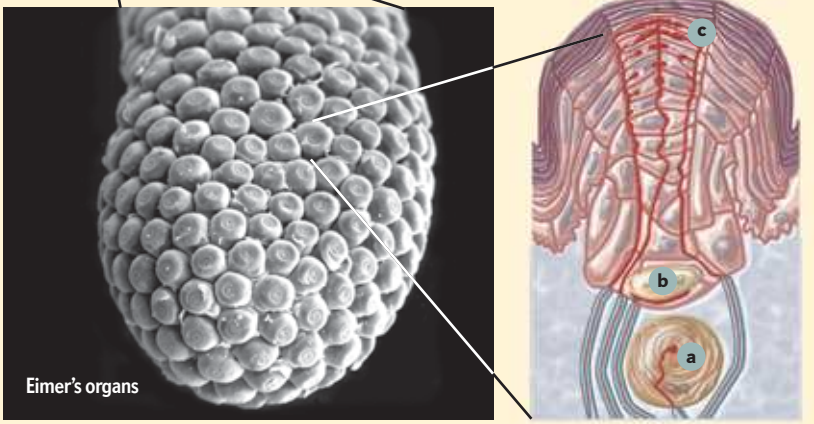


Cortical maps of the star-nosed mole reveal the importance of the 11th appendage. As this schematic shows, the most sensitive appendage gets the most space in the cortex (*above*). The same is true for the most sensitive part of the human eye. The organization of the cortex also beautifully mirrors the position of the appendages (*right*) and their relative importance.





Appendages of the star are made up entirely of sensory organs. These Eimer's organs have elements that are common to many animals' skin receptors: a single nerve ending at the very base **a**, which relays information about vibrations and initial contact with an object, and another nerve fiber that records sustained pressure **b**. But the very tip of the Eimer's organ is found only in moles: neural swellings arrayed just below the outer skin, which are amazingly sensitive to the details of surfaces **c**.



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When we compared the sizes of cortical brain maps with the appendages of the star, we noticed an obvious discrepancy. The 11th appendage, which is one of the smallest parts of the star, had by far the largest representation in the cortex. The discrepancy is a classic example of what has been termed cortical magnification: the most important part of the sensory surface has the largest representation in the brain, regardless of the actual size of the sensory area on the animal.

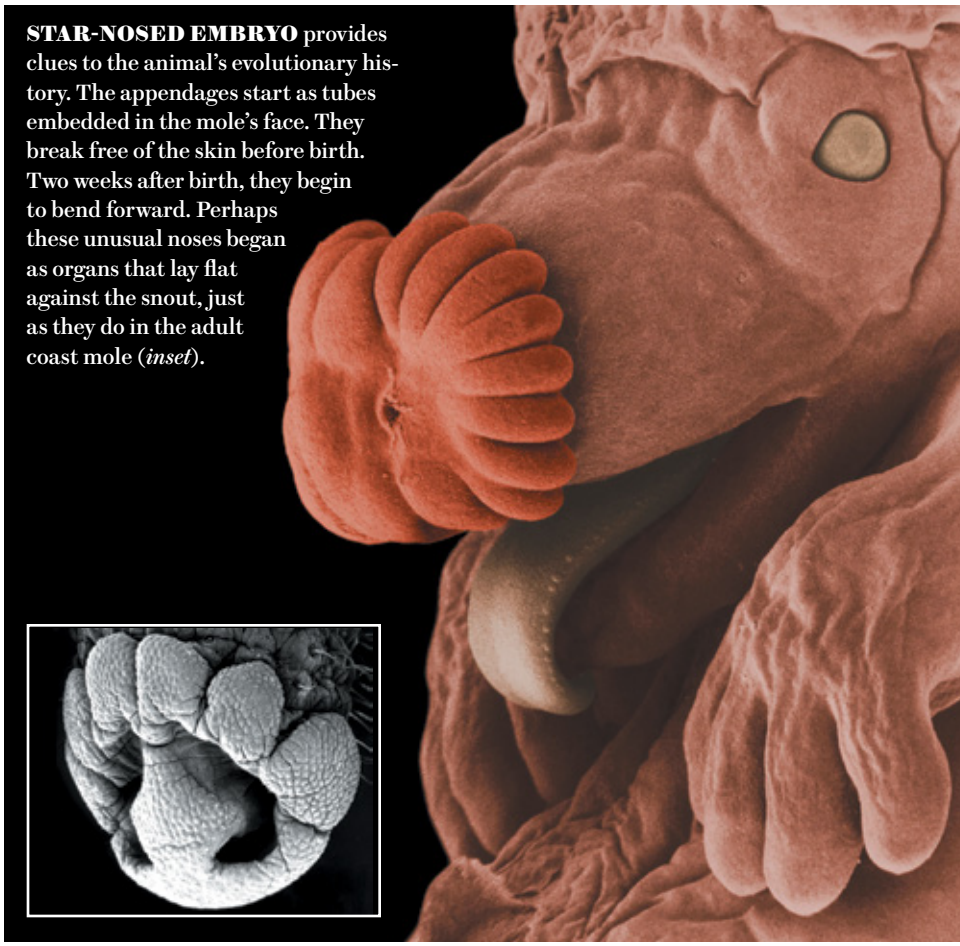
The same phenomenon occurs in the visual system, in which the small retinal fovea has by far the largest portion in visual cortex maps. We also discovered that neurons representing the 11th appendage responded to tactile stimulation of very small areas, or receptive fields, on the 11th appendage, whereas neurons representing the other appendages responded solely to stimulation of larger areas. The smaller receptive fields for the 11th appendage reflect a greater acuity for this region and mirror the organization of visual systems.

The discovery of a somatosensory fovea in the star-nosed mole suggests that this organizational scheme is a general evolutionary solution to constructing a high-resolution sensory system. Visual systems with a fovea are the most familiar, but auditory systems can have an acoustic fovea as well, as has been elegantly demonstrated in mustached bats by Nobuo Suga of Washington University in St. Louis. Many bats emit an echolocation call that contains a narrow frequency range and then analyze returning echoes to navigate and to detect prey. A large proportion of the bat's auditory receptors (hair cells in the cochlea) and large areas in the bat's brain are devoted to analyzing a narrow frequency range corresponding to a single harmonic of the returning echo. This is an example of an acoustic fovea.

Although it is hard to imagine, bats have an auditory version of a saccade as well. This is necessary because returning echoes are Doppler-shifted to different frequencies—depending on the speed of the bat and its target, usually an unfortunate insect—and often fall outside the frequency range of the acoustic fovea. Because the hunting bat cannot change its acoustic fovea, it constantly changes the frequency of its outgoing pulses so that the Doppler-shifted returning echo will be at the frequency of its acoustic fovea. The behavior is called Doppler-shift compensation and is the acoustic equivalent of moving the eyes, or the star, to analyze a stimulus with the high-resolution area of the sensory surface and the corresponding computational areas of the brain.

The presence of a sensory fovea in the mammalian visual system, auditory system and somatosensory system is a dramatic case of convergent evolution and points to common constraints in the way evolution can construct a complex brain. After all, why not just wire the entire sensory system for high-resolution input and eliminate the need to constantly shift the eyes, star or echolocation frequency? One reason, of course, is that it would take a massive enlargement of the brain—and the nerves carrying sensory inputs to it—to accomplish this task.

It is staggering to consider just how much larger the human brain would have to be if the entire retina were to have the same resolution as the fovea. To accomplish this, the human brain would have to be at least 50 times bigger. Your head would no longer fit through a doorway. Clearly, it is more efficient to devote a large part of the computational resources of the brain to a small part of the sensory system and then to move that area around like a spotlight to analyze important aspects of the world.



STAR-NOSED EMBRYO provides clues to the animal's evolutionary history. The appendages start as tubes embedded in the mole's face. They break free of the skin before birth. Two weeks after birth, they begin to bend forward. Perhaps these unusual noses began as organs that lay flat against the snout, just as they do in the adult coast mole (*inset*).

KENNETH C. CATANIA (*micrographs*)

SPACE RACE IN THE BRAIN

AS OFTEN OCCURS, our observations about the star-nosed mole's sensory system raised as many questions as they answered. How does part of a sensory surface acquire such a large section of the brain's map in the first place? The traditional understanding has been that each sensory input acquires the same average amount of area in a cortical map during development, and thus the enlarged representation of a sensory fovea simply reflects the greater number of neurons collecting information from the foveal region. This theoretical framework, suggesting that each input has equal squatter's rights in the brain, is appealing in its simplicity.

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But a number of studies challenged this democratic assessment of cortical parcellation in the primate visual system by showing that inputs from the fovea are allocated more cortical territory than those containing peripheral information.

To see what was happening in the star-nosed mole, we decided to measure the cortical representations of the 22 appendages and to compare those areas with the number of nerve fibers collecting information from each appendage. It was obvious (after counting more than 200,000 nerve fibers!) that sensory neurons collecting information from the 11th appendage are granted far more cortical territory in the brain maps than inputs from the other appendages. This is another parallel between the mole's somatosensory system and primate visual systems, and it shows not only that important areas of a sensory surface can have the highest number of sensory neurons collecting information per unit area but also that each of these inputs can be allocated extra computational space in the brain.

A STAR-NOSED MOLE CAN FIND AND EAT FIVE SEPARATE PREY ITEMS IN A SINGLE SECOND.

This observation, however, does not explain how these sensory inputs manage to take the most territory in cortical maps. The question belongs to one of the most fascinating areas of research in neuroscience because changes to cortical maps could be a critical component of learning complex skills and recovering from brain injuries or strokes. Several studies indicate that a combination of intrinsic developmental mechanisms and experience-dependent plasticity affects the shape and maintenance of brain maps.

These findings are especially intriguing in the case of the star-nosed mole because the pattern of use of the nose—as measured by how the mole touches prey with the different appendages—very closely matches the pattern of magnification for the appendage representations in the cortex. The correspondence suggests that behaviors may shape the way the cortex is organized. Alternatively, intrinsic developmental mechanisms may match the size of cortical maps to their behavioral significance. It is the classic question of nature versus nurture.

THE DEVELOPING STAR

LOOKING AT HOW the star develops in mole embryos can help clarify this matter. Because the star develops before its representation in the cortex, sensory inputs from the star have an opportunity to influence the way that the cortical maps form during potentially critical periods of development.

Star-nosed mole embryos come in about the strangest-looking varieties imaginable. Although most embryos look odd, star-nosed moles appear especially weird because the embryonic hands are gigantic—all the better to dig with later—and the nose is obviously unique.

Studies of the embryos revealed that appendage 11 was the largest appendage during early development, despite its relatively small size in adults. It also became clear that Eimer's organs on the star, and the neural structures within each Eimer's organ, matured first on the 11th appendage. It is as if this appendage gets a head start compared with all the other ones, which later overtake it in size and number of Eimer's organs. As it turns out, the retinal fovea in the visual system also matures early.

When we examined the corresponding patterns in the somatosensory cortex, we found that markers for metabolic activity appear first in the representation of the 11th appendage. This suggests that the early development of the fovea results in greater activity in the developing cortical representation of this area, which could allow these inputs to capture the largest area in the cortical map. Strong evidence from the developing visual system of primates indicates that sensory inputs with the greatest level of activity are able to capture the largest areas in the cortex during development. But it is also possible that early behavioral patterns in star-nosed moles—which use the 11th appendage to suckle—contribute to activity-dependent expansion of the fovea in the cortical maps.

HOW THE MOLE GOT ITS STAR

ONE CAN'T HELP but wonder how the star-nosed mole evolved. Examining the embryos provided a road map to star-nosed mole evolution—or at least to that of its enigmatic nose. The appendages that form the star develop unlike any other known animal appendage. Rather than growing directly out of the body wall, the star appendages form as cylinders, facing backward and embedded in the side of the mole's face. In the course of development, these slowly emerge from the face, break free from the skin and then, about two weeks after birth, bend forward to form the adult star. The backward developmental sequence suggests that ancestral star-nosed moles might have had strips of sensory organs lying flat against the sides of the snout. These might have been slowly raised up over many generations until the star was formed.

Of course, without further evidence, this might remain a "Just So" story. But there exist two mole species—the coast mole (*Scapanus orarius*) and Townsend's mole (*S. townsendii*)—that have short strips of sensory organs lying flat against the upper side of their noses, and these adult noses bear an uncanny resemblance to the embryonic star. These intermediate forms strongly suggest that such an ancestor gave rise to the full-fledged star we see today. However they came to be, these unlikely noses may help reveal much about the influence of innate developmental mechanisms and behavioral patterns on the organization of the cortex. SA

Kenneth C. Catania first encountered star-nosed moles when he worked at the National Zoo in Washington, D.C., many years ago. Catania, who is Stevenson Professor of Biological Sciences at Vanderbilt University, studies the sensory system of mammals and the organization of the neocortex. He received his undergraduate degree in zoology from the University of Maryland and his Ph.D. in neuroscience from the University of California, San Diego. Catania has received the Capranica Foundation Award in Neuroethology and the International Society of Neuroethologists/ Young Investigator Award and is a Searle Scholar.

MORE TO EXPLORE

The Natural History of Moles. Martyn L. Gorman and R. David Stone. Cornell University Press, 1990.

Sensory Exotica: A World beyond Human Experience. Howard C. Hughes. MIT Press, 1999.

A Nose That Looks Like a Hand and Acts Like an Eye: The Unusual Mechanosensory System of the Star-Nosed Mole. K. C. Catania in *Journal of Comparative Physiology*, Vol. 185, pages 367–372; 1999.

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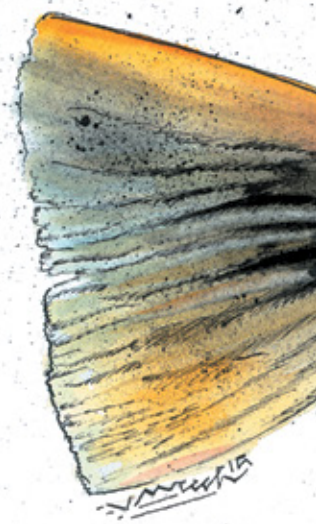
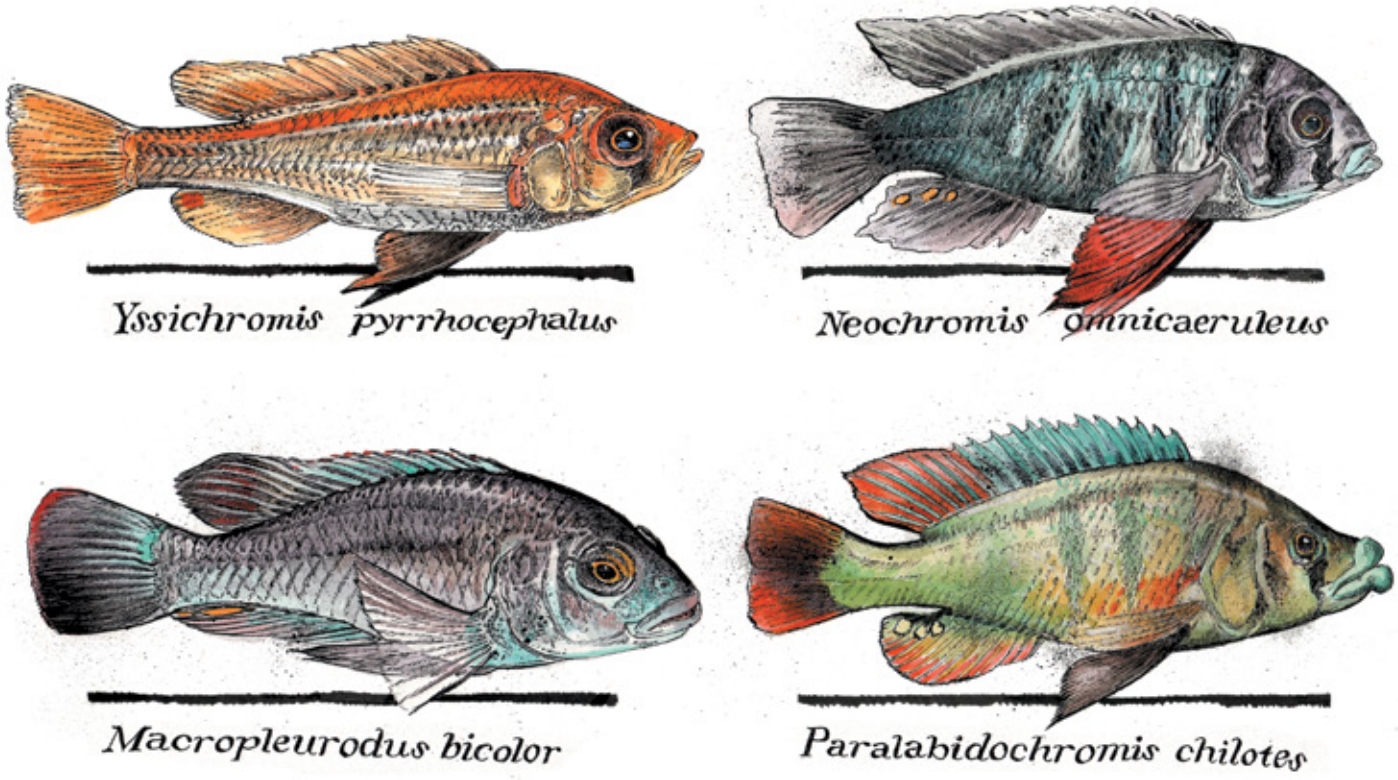
EXTREME EVOLUTION



Cichlid fishes have undergone a mind-boggling degree of speciation. New research is revealing features of their genomes that primed them to diversify so spectacularly

By Axel Meyer

ASTONISHING VARIETY of cichlid fishes live in East Africa's Lake Victoria. The 500 or so species, representative examples of which are shown here, are thought to have evolved within the past 15,000 years—a remarkably short period.



Illustrations by Jack Unruh

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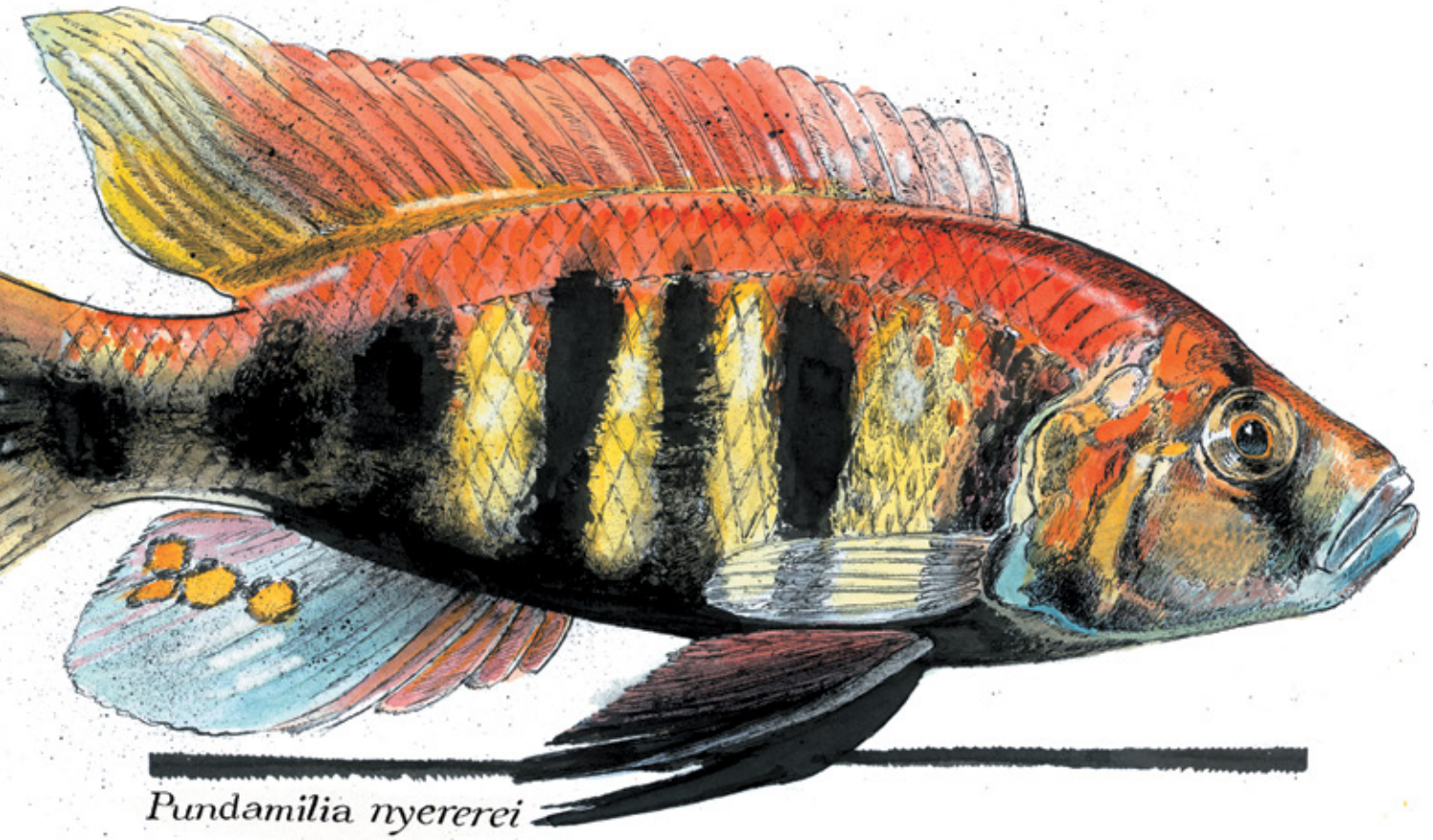
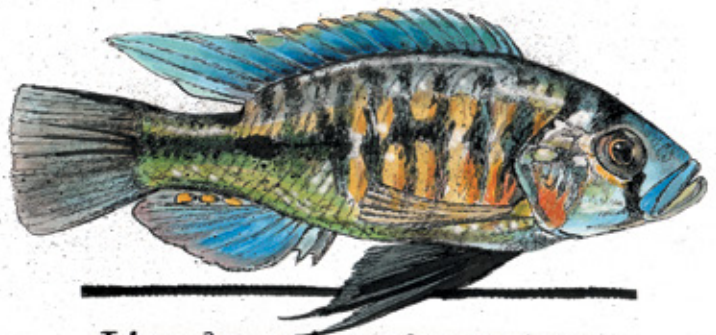
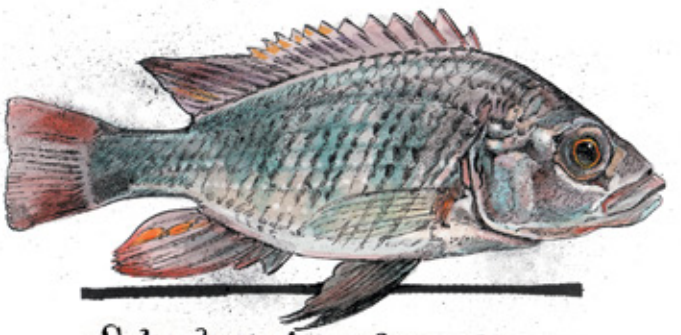


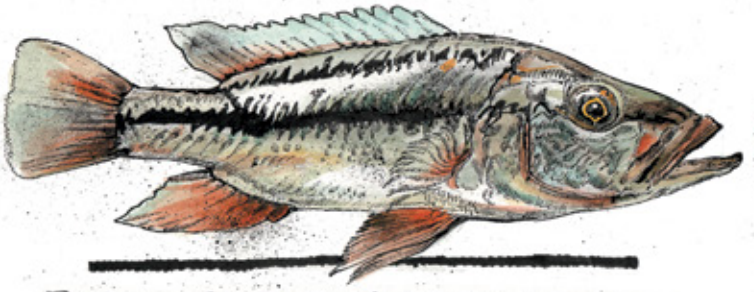
Pundamilia nyererei



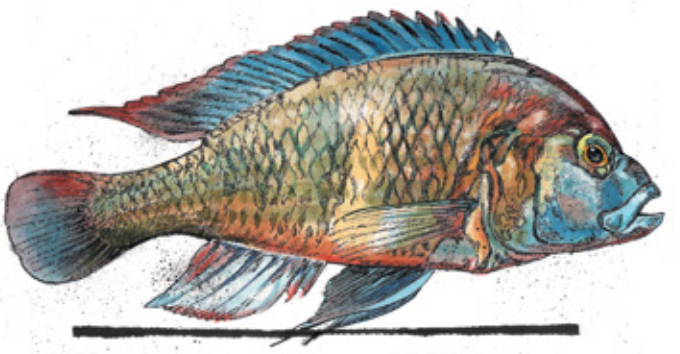
Lipochromis melanopterus



Schubotzia eduardiana



Prognathochromis macrognathus



Thoracochromis pharyngalis

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AFRICA'S LAKE VICTORIA IS HOME TO ONE OF EVOLUTION'S GREATEST experiments. In its waters, what began as a single lineage belonging to the cichlid family of fishes has since given rise to a dazzling array of forms. Like Charles Darwin's famous finches, which evolved a wide range of beak shapes and sizes to exploit the different foods available in the Galápagos Islands, these cichlids represent a textbook example of what biologists term an adaptive radiation—the phenomenon whereby one lineage spawns numerous species that evolve specializations to an array of ecological roles. But the Lake Victoria cichlids far surpass Darwin's finches in the astonishing speed with which they diversified: the more than 500 species that live there and only there today all evolved within the past 15,000 to 10,000 years—an eyeblink in geologic terms—compared with the 14 finch species that evolved over several million years.

Lake Victoria is not the only locale cichlids call home. Other tropical freshwater lakes and rivers in Africa, as well as the Americas and the tip of the Indian subcontinent, harbor their own cichlids. All told, the family is estimated to comprise more than 2,500 species. Some, such as the tilapias, are farmed for food and are among the most important aquaculture species in the world. Most, like the oscars and angelfish, are popular with aquarium enthusiasts because they are beautiful and have many interesting courtship and parenting behaviors. Many species have yet to be formally described. The cichlids share their lakes with other families of fishes, but only cichlids have managed to speciate so extensively and so fast. Indeed, no other group of vertebrate animals can rival the cichlids in terms of sheer number of species and variety of body shape, coloration and behavior. At the same time, however, evolution has often repeated itself in these fishes: a number of the same adaptations have evolved in parallel in the separate cichlid lineages—a curious trend.

I and other scientists have long marveled at the manifold forms of cichlids and wondered what factors allowed this group to differentiate in such spectacular fashion. Recent advances in genome-sequencing technology have allowed us to comb their DNA for clues to this evolutionary exuberance. We have not solved the full puzzle of cichlid diversity yet—far from it. But we have found some special characteristics of cichlid genomes that might have primed them to diversify with such speed yet also to evolve certain traits again and again. As we explore the genetic underpinnings of the extraordinary success of this group of fishes, we are glimpsing the very cogs and wheels of evolution—insights that will help researchers decode the origins of all manner of species.

DIFFERENT BUT THE SAME

TO GET A CLEARER PICTURE of just how amazingly diverse cichlids are, consider the forms in Lake Victoria and the two other lakes in which the major East African cichlid radiations occurred: Lake Malawi, which harbors perhaps 800 to 1,000 species, and Lake Tanganyika, with its roughly 250 species from older cichlid lineages, one of which colonized the other two younger lakes and spawned the radiations there. These cichlids display every rainbow hue and range from about an inch to three feet in length. And they have evolved adaptations to eating every conceivable food source in their environment. Algae scrapers have flat teeth like human incisors that allow them to nibble the nutritious growths on rock surfaces; insect eaters have long, pointy teeth that help them to get into rock crevices; ambush predators possess huge extendable jaws with which they can suck in their unsuspecting prey in a matter of milliseconds. Those are just some of the broader categories of specialization. Among the algae scrapers, for instance, some species are adapted to foraging in the wave-break zone, others to harvesting food from one particular pile of rocks and no other, and still others to feeding on certain angles from the rocks or only on specific types of algae.

And yet for all the variety seen in the East African cichlids, some highly specialized traits have evolved repeatedly—to a surprising degree. For instance, several species of cichlids in all three lakes feed almost exclusively on the scales of other fishes. They have all developed the same distinctive rakelike teeth that allow them to hold on to the scales of their victims. But their teeth are not the only adaptation to this diet. Their jaws have evolved to be asymmetrical, opening either to the left or to the right, but not both, so as to better grab the scales from a given

IN BRIEF

Cichlid fishes are the most diverse family of vertebrate animals on record, with more than 2,500 species.

The recent sequencing of several cichlid genomes has begun to furnish clues to their astounding diversification.

Cichlid genomes exhibit a number of special features that may have accelerated the evolution of this group.

Other genome traits may explain cichlids' tendency to independently evolve the same adaptations repeatedly.

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side of their targets. "Left-headed" cichlids rasp the scales from the right side of their victim; "right-headed" ones scrape from the left. (Natural selection has kept these asymmetrical forms in balance: about half of the scale eaters that my colleagues and I collected around Lake Tanganyika were right-headed, and the other half were left-headed.) The scale eaters have a very particular set of adaptations to their way of life, but somehow these same traits have arisen at least three separate times in these East African lakes.

Another distinctive adaptation that has emerged independently multiple times is enlarged lips in species that target prey found in rock crevices. My colleagues and I have shown that these "Angelina Jolie" lips act as seals and bumpers that help the fishes suck prey out from their hiding spots. (Cichlids lacking such lips cannot reach prey efficiently in narrow crevices.) Remarkably, species in all three African radiations, as well as two New World radiations, have developed this trait in parallel.

Similarly, distinctive coloration patterns have evolved independently in several separate cichlid lineages. Whereas the vast majority of cichlids sport dark, vertical stripes that presumably camouflage them from predators, a handful of species from each of the three East African lakes also evolved horizontal stripes. This strikingly different patterning occurs mostly in open-water species that tend to be fast swimmers and predators, possibly because the horizontal stripes help to obscure their body shapes from watchful prey.

KEY INNOVATION

One Secret to Success: Backup Jaws

All cichlids have the usual mouth jaws, but they also possess a second set of jaws located in the throat. The food they eat gets broken down by both sets of jaws. This duplication leaves the mouth jaws free to evolve adaptations to particular kinds of sustenance—from algae to the scales of other fishes—without risk of a species becoming dangerously dependent on any given food source that could run out.

ENGINES OF INNOVATION

THE SEEMINGLY contradictory themes of extreme diversification and repeated parallel evolution of ultraspecialized adaptations in cichlid evolution raise several key questions. One begins with the highly specialized eaters and the observation that, ordinarily, adapting to a narrow diet means that if something goes wrong with the needed food source, the specialist is in trouble. So how have the cichlids managed to avoid falling into that trap? One answer seems to be a strange anatomical feature that cichlids alone possess among freshwater fishes. All cichlids have a normal pair of mouth jaws and a second pair of jaws located in the throat, like the monster in the movie *Alien*. Any food they eat gets grabbed and processed first by the mouth jaws and second by the throat jaws. As a result, cichlids can have mouth jaws adapted to one kind of food, and their throat jaws can break down other stuff. In this novel way, many cichlids have become jacks-of-all-trades, masters-of-one. In other words, they can evolve a specialization but remain generalists at the same time in case their preferred food runs out or a better option becomes available.

The throat jaws explain how cichlids have been able to mitigate the risk of specializing, but what was the source of all the evolutionary novelty in these fishes? What were the factors that spurred the genes that encode their traits to change so rapidly, and how did the same adaptations keep turning up in separate lineages? Recently, thanks to the advent of fast genome-sequencing methods for health research, my colleagues and I—a consortium of more than 70 researchers from laboratories around the world, led by the Broad Institute in Cambridge, Mass.—have begun making inroads into answering these questions and solving the riddle of the cichlid family's stunning success. In 2014, for the first time, we decoded the sequence of DNA code letters in cichlid genomes. We obtained complete sequences for five African species and partial sequences for 60 individuals representing six very closely related species from Lake Victoria alone. By comparing these genomes with one another and with those of the cichlids' relatives, the sticklebacks—a far less diverse family of fishes—we have been able to identify features of cichlid genomes that help to explain the group's diversity.

Among the first things the Cichlid Genome Consortium looked for in these genomes were mutations that have produced changes in the amino acids that make up proteins; proteins do much of the work in cells, and many genes specify the sequence of amino acids that get strung together to generate a given protein. An overabundance of proteins containing altered amino acids would suggest that the genes harboring the underlying mutations were under strong selection pressure to evolve quickly; that is, conditions were such that fishes that acquired certain amino acid changes thereby gained a strong survival or repro-

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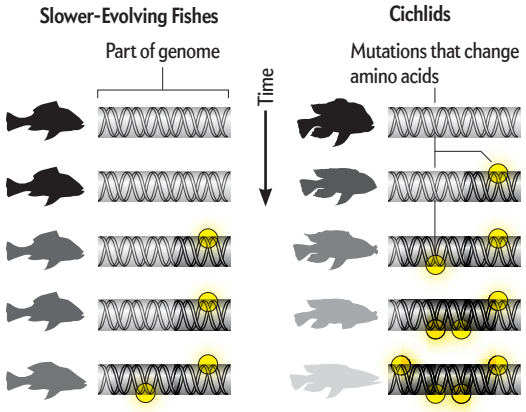
NEW FINDINGS

Genome Clues

The recent sequencing and analysis of genomes from African cichlids has revealed a number of mechanisms that may have spurred cichlids to quickly diversify into myriad forms. Some of these mechanisms could also help explain another mysterious aspect of this group of fishes: namely the extreme degree of parallel evolution, in which the same highly specialized traits emerged again and again.

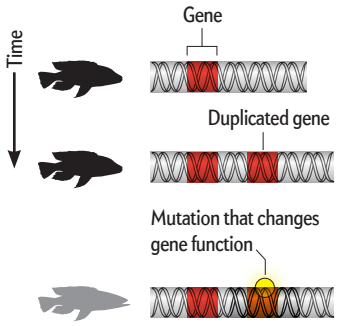
Abundant Mutations

A surfeit of mutations that produced changes in the amino acids that make up proteins suggests the genes harboring these mutations were under intense selection pressure to evolve quickly.



Gene Duplication

Cichlid genomes exhibit a high rate of gene duplication, in which errors in DNA replication produce multiple copies of genes. The extra copies can change in function without harming the fishes and can thus help them adapt to their environment.



ductive advantage. We found that even the tilapia species we sequenced, which is an evolutionarily unremarkable cichlid compared with its brethren, had more such mutations than the sticklebacks. And the cichlids from the hyperdiverse groups in Lake Malawi and Lake Victoria had mutation rates several times higher than the tilapia's. Many of the affected genes are known to be involved in jaw development, which makes sense, given the range of dietary adaptations seen in cichlids. Thus, one mechanism that has hastened cichlid speciation is intense selection pressure acting on many genes.

But individual genes can have great power, too. My laboratory has found evidence that a single gene determines the orientation of the stripes on the cichlids. Genes that on their own make a huge difference in an organism's appearance, as the stripe coders do, could help explain why there are so many kinds of cichlids.

We were also eager to survey the cichlid genomes for multiple copies of individual genes. Scientists have known for decades that duplication of genes—which arise from errors in DNA replication—is one of the most important mechanisms by which gene function can rapidly diversify. In essence, if a gene were duplicated, the new copy might be free to change without denying the animal any of the material encoded by the gene (because the other copy would still work), and the change could potentially help the creature to adapt to its environment. Typically genes are quite constrained in the mutations that can occur without harming the "host." Our genome analyses show that cichlids have rates of gene duplication that are up to five times higher than that of "normal" fishes such as the sticklebacks.

A third type of genomic mechanism we sought to analyze was the activity of so-called jumping genes. Around 16 to 19 percent of the genome of a typical fish is made up of such DNA sequences, which do not serve an obvious function but make copies of themselves and jump from one location in the genome to another. They can be a force of evolution if they insert themselves close enough to a protein-coding gene to change its function. In the cichlid genomes, we have found telltale signs of several periods in which jumping genes accumulated rapidly, including one that coincided with the Lake Victoria radiation. The timing suggests that jumping genes may have helped facilitate the diversification of cichlids during such events.

We also examined DNA sequences that ordinarily do not change much. Certain regions of the genome that do not specify amino acids in proteins tend to be highly conserved across large evolutionary time spans. These conserved noncoding elements (CNEs), as they are known, probably affect the functioning of genes. Otherwise, random mutations would accumulate, as they typically do over time in nonconserved regions, rendering these regions different from species to species. Cichlids share a number of CNEs with one another and with more distantly related species, such as sticklebacks. But when we took a closer look at the DNA, we found that although the cichlid CNEs are similar enough from species to species to spot them, they have changed more than one would expect for CNEs. Our cichlid genome comparisons found that about 60 percent of the CNEs had undergone significant changes in particular lineages of cichlids. This surprisingly high percentage suggested that the genes to which these CNEs are linked might have undergone a change in function. Subsequent experiments bore this hunch out: researchers assessed the function of conserved and altered cichlid CNEs by inserting this genetic material into the genomes of zebra fish and found that the altered CNEs switched on their associated genes differently than the unaltered CNEs did—a sure sign that evolution of the CNEs led to changes in gene function in cichlids.

Another kind of genetic material that tends to be highly conserved across species is microRNA. MicroRNAs are small molecules that act as switches for genes, telling them where and when they should do their work. We were surprised to find 40 that had never been seen before in other fishes. We then studied cichlid embryos to see where in the body some of these microRNAs were regulating gene activity. It turns out they work in a highly specific manner, influencing genes only in certain tissues, such as a particular region of the facial skeleton. The targeted activity of microRNAs hints that they could have enabled the kind of precision sculpting that gave rise to the vari-

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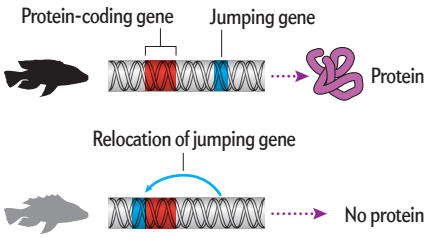
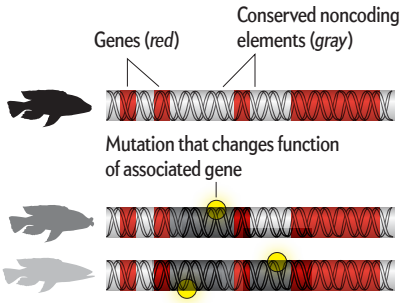
Jumping Genes

Sequences of DNA that make copies of themselves and jump to new positions in the genome are called transposable elements, or jumping genes. Depending on where the jumping gene lands, it may change the function of a nearby protein-coding gene. Cichlids underwent several periods in which jumping genes accrued rapidly, possibly hastening evolution.



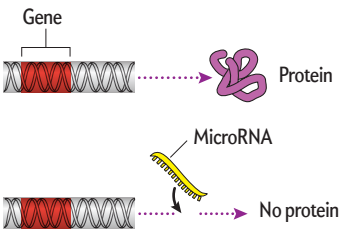
Mutations in DNA That Typically Does Not Change

Some genome regions that do not encode proteins tend to be highly conserved in evolution, probably because they affect gene function. Cichlids have significantly more mutations in some of these regions than expected, exhibiting a pattern that suggests the associated genes experienced a shift in function.



Novel MicroRNAs

Small pieces of genetic material called microRNAs, which can block genes from doing their job of making proteins, also tend to be conserved. Cichlids have more new microRNAs than other fishes have. With their ability to control genes in particular tissues, these microRNAs may have enabled the precise sculpting that gave rise to cichlid feeding specializations.



ous feeding specializations cichlids possess, among other traits.

We remain a long way from fully understanding if and how all the hundreds of microRNAs in cichlid genomes actually foster evolutionary change, but they are strong candidates for such a role. We hypothesize that by preventing genes from being switched on at the wrong place or time, microRNAs could encourage both more variation and more precision in orchestrating the intricate ballet of genes that interact to make slightly different teeth, jawbones, color patterns, courtship behaviors, and so on—variation that is the basis for adaptation and speciation.

WHAT'S OLD IS NEW

THIS INITIAL FORAY into cichlid genomes suggests that new random mutations, such as those seen in the CNEs and those that give rise to novel microRNAs, have figured significantly in the extraordinary evolution of these fishes. But we suspect that relatively old genetic variation, including that from duplicated genes and jumping genes, may have done most of the work. These variants lurked quietly in the genome until new ecological opportunities—for instance, those that arose when ancestral river-dwelling cichlids colonized the Great Lakes of Africa—suddenly made them advantageous. By tapping into that ancient genetic variation, natural selection created species suited to the new habitats.

We think old variation is the key because when we look at the genomes of these cichlid species, we cannot find many fixed genetic differences between them. That is, there are very few examples of genes for which all members of a species carry the same variant. Instead the gene pool of a species retains old gene variants even after fish have branched off from their ancestors to form a new species. And not only does a young species retain old DNA from its ancestors, but it may still be similar enough to interbreed and hybridize with closely related species. Such mixing would allow new gene variants to flow across species boundaries—more potentially useful genetic material that can be recycled when needed. The retention of old genetic variation, in addition to fueling rapid diversification in cichlids, can also help explain how the same ultraspecific traits have evolved over and over in separate lineages: we suspect that traits such as asymmetrical jaws and Angelina Jolie lips may not have arisen anew each time; rather the same genes and gene switches were repeatedly recruited into service. This hypothesis awaits testing.

The genomic mechanisms described here were not the only drivers of cichlid evolution. Surely environmental factors had a crucial part in establishing the patterns and rates of diversification in this group. Differences in the extent of cichlid diversity in the various radiations of these fishes around the world support this surmise: in Africa and in Nicaragua, the radiations that occur in lakes with more complex habitats (and thus more ecological niches) have more species than the radiations in lakes with simpler habitats. In addition to the speciation that occurred as cichlids evolved feeding specializations to fill these niches, further diversification took place as skin color differences arose and females developed preferences for particular hues.

We still have much to learn. Now that we have complete genomes, as well as powerful new techniques for analyzing them, though, our knowledge will advance very quickly indeed. I expect that the mechanisms underlying the speed of cichlid speciation will continue to be an area of intense research. Soon we will have a far deeper understanding of the language of the genome and the DNA that connects all living things even as it drives them apart. SA

Axel Meyer is a professor of zoology and evolutionary biology at the University of Konstanz in Germany. His research focuses on the origins of adaptations and biodiversity at both the molecular and organismal levels. He was among the first scientists to use DNA sequences to study species differences and speciation.

MORE TO EXPLORE

The Evolutionary Genomics of Cichlid Fishes: Explosive Speciation and Adaptation in the Postgenomic Era. Frederico Henning and Axel Meyer in *Annual Review of Genomics and Human Genetics*, Vol. 15, pages 417–441; August 2014.

The Genomic Substrate for Adaptive Radiation in African Cichlid Fish. David Brawand et al. in *Nature*, Vol. 513, pages 375–381; September 18, 2014.

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Illustration by Jen Christiansen

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SECRET LIVES OF ANIMALS

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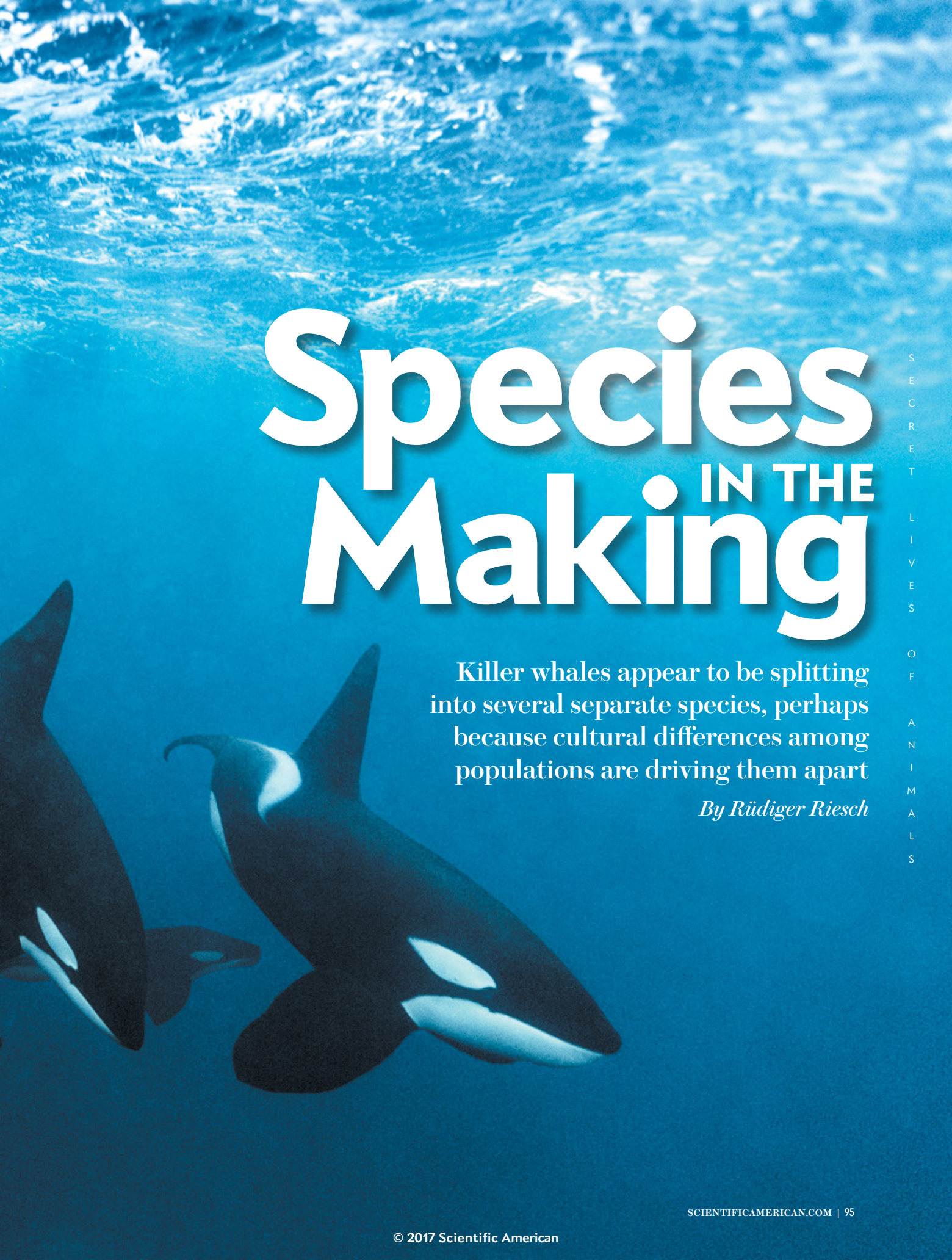

Species IN THE Making

SECRET LIVES OF ANIMALS

Killer whales appear to be splitting into several separate species, perhaps because cultural differences among populations are driving them apart

By Rüdiger Riesch

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JUST OFFSHORE FROM THE PEBBLE BEACHES OF BERE POINT ON MALCOLM ISLAND, British Columbia, the *Naiad Explorer* rocks gently in the waters of the Queen Charlotte Strait. The sun has burned off most of the morning mist, save for a thin layer that still shrouds the tips of the island's cedars, firs and spruces. I watch from the boat as three killer whale brothers named Cracroft, Plumper and Kaikash gently scrape their bodies against the small, smooth stones in the shallows off the bow. The brothers have already spent the better part of an hour here absorbed in this activity. Soon they will leave to hunt for salmon or look for mates. Exactly why the creatures engage in this scraping behavior, known as beach rubbing, is uncertain. Most experts assume that it aids in sloughing off dead skin and dislodging external parasites, but it might also be for pleasure. Whatever the motivation behind it, beach rubbing, though rarely observed in other cetaceans—the group that includes whales, dolphins and porpoises—is commonplace here. It is part of the distinctive cultural fabric of the northern resident killer whales, a community that claims the waters around northern Vancouver Island as home during the summer months. (Despite their name, killer whales are actually large dolphins.)

The northern resident killer whales are not the only ones with unique behaviors. Observations made since the 1970s have shown that killer whale populations around the globe each have unique ways of doing everything from hunting to communicating. Physical traits, including coloration, body size and dorsal fin shape, vary among groups as well, albeit somewhat more modestly. These cultural and physical differences, along with the astonishing degree of genetic diversity documented in these creatures over the past 15 or so years, suggest to me and many other researchers that today's killer whale populations, rather than simply representing the single species scientists have long envisioned, are actually in the midst of going their separate evolutionary ways. That is, they appear to be splitting into new species that, if this process continues, ultimately will be unable to produce viable or fertile offspring with one another.

Intriguingly, their cultural differences may be driving this diversification: the whales seem to mate with individuals that largely share their customs, to the exclusion of those that do not, a preference that creates the conditions needed for speciation to occur. If so, then killer whales could provide a striking example of a speciation mechanism not considered in the classical theory of how new species arise. They might also offer insights into how another group of creatures—*Homo sapiens* and our extinct predecessors—diverged into an array of species that once shared the planet.

A DIVERSITY OF KILLERS

FOR MORE THAN A CENTURY biologists have looked to geography to explain how speciation occurs. In the favored scenario, called allopatric speciation, two populations of an ancestral species become physically separated from each other, often by a geographical barrier of some kind—perhaps a mountain range, desert or river—that prevents the populations from interbreeding. If this separation persists long enough, over time each pop-

IN BRIEF

Evolutionary biologists have long turned to geography to explain the emergence of new species.
In the classic explanation, two populations of an ancestral species become separated by a geographical barrier that prevents them from interbreeding, thereby allowing each group to follow its own evolutionary trajectory.
Killer whale populations appear to be going separate evolutionary pathways despite the fact that no known geographical barriers separate them.
Mounting evidence indicates that cultural differences related to food acquisition are driving these populations apart.
The killer whale findings raise questions about diversification within another culture-bearing group of organisms: members of the human family.

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ulation will follow its own independent evolutionary trajectory, acquiring different genes that may help them survive in different environmental conditions, for example, or that may accumulate randomly through a process known as genetic drift. Eventually, so the theory goes, the two populations can become so genetically different from each other that if they come into contact again, they cannot interbreed successfully.

Overwhelming evidence from numerous organisms ranging from species of *Alpheus* snapping shrimp that live on either side of the Isthmus of Panama to *Cyprinodon* pupfish species found only in isolated springs in California and Nevada shows that geographical isolation does indeed facilitate the speciation process. Yet sometimes two or more subpopulations of dissimilar appearance will emerge within the same geographical area and ultimately differentiate into separate species. Scientists, including famed German evolutionary biologist Ernst Mayr, traditionally held that at least some period of isolation was essential to the process of speciation and that speciation entirely within the same area was therefore either impossible or at least very rare. More recent work has demonstrated that geographical isolation in the traditional sense is not always necessary for speciation to occur, however.

Indeed, biologists now largely accept that certain species, among them the astonishingly diverse cichlid fishes found in the lakes of East Africa and Nicaragua, as well as the *Howea* palm trees found on Lord Howe Island in the Pacific, have evolved in the absence of such isolation. In the parlance of biologists, they have undergone sympatric speciation, and in the case of cichlids, this was apparently mostly driven by different cichlids adapting to exploit different food sources (but without the influence of culture), whereas different Lord Howe palms have evolved different flowering times. Documented examples of sympatric speciation among mammals are rare, though, which makes the case of the killer whales especially interesting.

Killer whales (also called orcas and, in some regions, blackfish) are the most widely distributed mammal on earth after humans. They inhabit all the world's oceans and can travel more than 100 kilometers a day or upward of several thousand kilometers within just a few weeks. There are no known geographical barriers that would prevent individuals from one population from mingling with members of neighboring populations. Yet scientists have now shown that in various marine areas, several ecologically distinct forms, or ecotypes, of killer whales live side by side without fraternizing. One type, for instance, might live mainly on a particular kind of fish, whereas another type might prefer seals.

The best-studied assemblage of killer whale ecotypes lives in the Northeast Pacific. There research begun in the early 1970s by Canadian scientist Michael Bigg led to many remarkable discoveries. First, he noticed that individual killer whales differed in the shape and size of their dorsal fins and in the shape, size and coloration of the so-called saddle patch—the grayish white area behind the dorsal fin. Biologists can use those traits to identify individual killer whales, just as forensic scientists use facial features and fingerprints to identify individual humans. Second, Bigg and his colleagues, including John K. B. Ford and Graeme M. Ellis, both at Fisheries and Oceans Canada, and Kenneth C. Balcomb III of the Center for Whale Research in Washington State, found that three different killer whale ecotypes coexist in the waters off the West Coast of the U.S. and Canada: the so-called resident, transient and offshore forms. Resident killer whales specialize in foraging for fish, especially salmon; transient killer whales target marine mammals and the occasional seabird; and offshore killer whales seem to specialize in a second kind of fish diet that includes Pacific halibut and Pacific sleeper sharks, although their habits remain largely mysterious because encounters with them are rare.

In recent years research led by Olga A. Filatova of Moscow State University, Alexander M. Burdin of the Russian Academy of Sciences, and Erich Hoyt of Whale and Dolphin Conservation in England has revealed that residentlike and transientlike ecotypes also share the Russian waters of the Northwest Pacific around the Kamchatka Peninsula. Thus, we now know that there is a more or less continuous band of resident populations coexisting with transient populations that connect the Northeast Pacific with the Northwest Pacific via the Aleutian Islands.

Halfway across the world, killer whale populations from around Iceland, Shetland and Norway in the Northeast Atlantic have their own food preferences. Scientists, including Volker B. Deecke of the University of Cumbria in England, Andrew D. Foote while at the University of Bern in Switzerland, and their colleagues, have reported on two groups: type 1 killer whale populations forage for fish, in particular herring and mackerel, and type 2 killer whales pursue seals. More research is needed to fully understand the dietary differences between the groups.

The Southern Hemisphere hosts geographically overlapping ecotypes, too. John W. Durban and Robert L. Pitman, both at the National Oceanic and Atmospheric Administration, and their colleagues have discovered at least four different ones in Antarctic and sub-Antarctic waters. "Type A" killer whales appear to specialize in hunting Antarctic minke whales, "type B" killer whales, on the other hand, come in a large form (the so-called pack ice killer whale) that focuses on seals and a small form (the Gerlache killer whale) that favors penguins. "Type C"—the smallest known killer whale—hunts Antarctic toothfish. For its part, "type D," like the offshore killer whales of the North Pacific, seems to be an open ocean ecotype that remains largely elusive. This ecotype is known to eat Patagonian toothfish from longline fisheries, but it probably dines on other prey as well.

Once scientists realized that all these factions existed within the killer whales, they began to wonder about the origins of these groups. Were the populations already living in the same geographical region when they started to differentiate, or did they start diverging at a time when they lived apart and only later colonized the same region after they had already started down separate evolutionary paths? Current evidence is mostly inconclusive for many Northern Hemisphere killer whales. Whereas several studies by Foote and his colleagues suggest that killer whale divergence in the North Pacific happened while populations were geographically isolated (allopatric speciation), other analyses by Alan Rus Hoelzel of Durham University in England and his collaborators hint that these ecotypes might have always coexisted (sympatric speciation). For the killer whales of the Antarctic, though, the evidence is clearer: most, if not all, of these killer whale ecotypes probably diverged sympatrically while living in the same geographical region.

However the now sympatric ecotypes initially began to diverge, they did so rapidly. In May 2016 Foote and his colleagues

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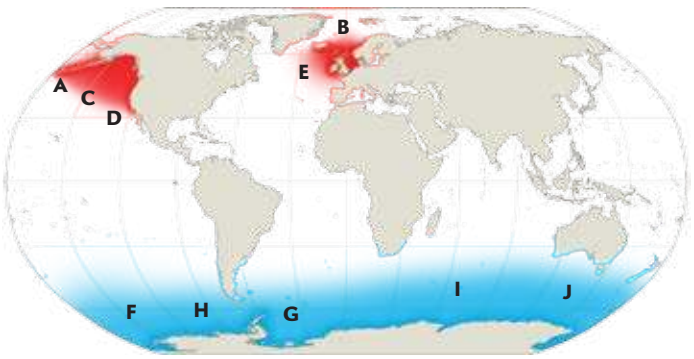
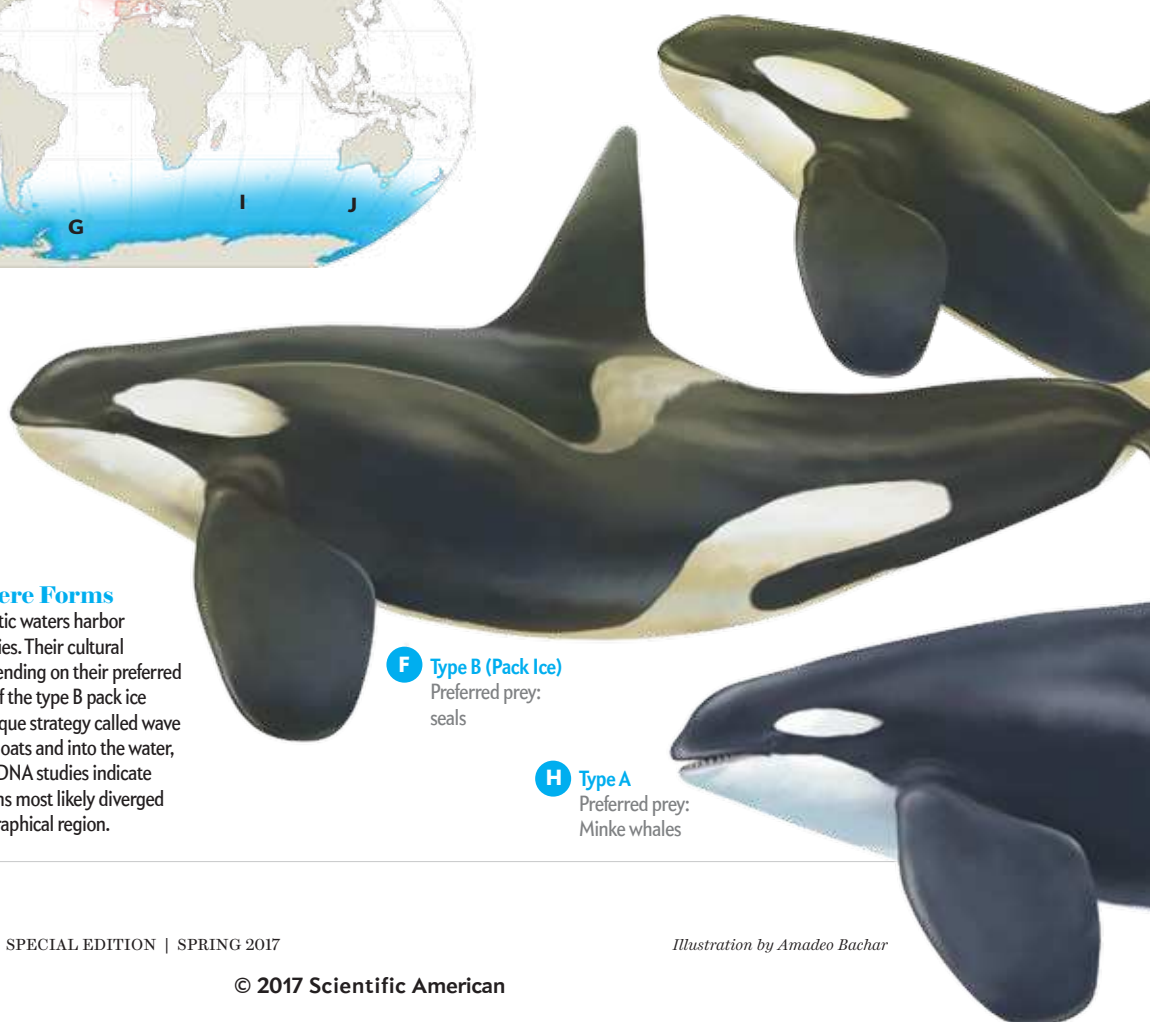
A Resident
Preferred prey: fish, especially salmon

Kinds of Killers

Killer whales live in all the world's oceans, without any geographical barriers to keep their populations from interbreeding. Yet studies show that in various regions distinct forms, or ecotypes, have arisen despite living in close proximity to one another. These separate groups, which do not interbreed, differ in their prey choices and how they hunt. They also differ in their physical features, such as body size and coloration, eye patch size, and the shape of the dorsal fin and the saddle patch behind it. The whales choose mates that share their customs rather than foreigners from other ecotypes. Culture appears to keep the ecotypes apart, promoting speciation.

B Type 1
Preferred prey: herring and mackerel





Southern Hemisphere Forms

The Antarctic and sub-Antarctic waters harbor at least five killer whale varieties. Their cultural traditions probably differ depending on their preferred prey. For instance, members of the type B pack ice ecotype have developed a unique strategy called wave washing to push seals off ice floats and into the water, where they are easier to nab. DNA studies indicate that the majority of these forms most likely diverged while living in the same geographical region.

F Type B (Pack Ice)
Preferred prey: seals

H Type A
Preferred prey: Minke whales

Illustration by Amadeo Bachar

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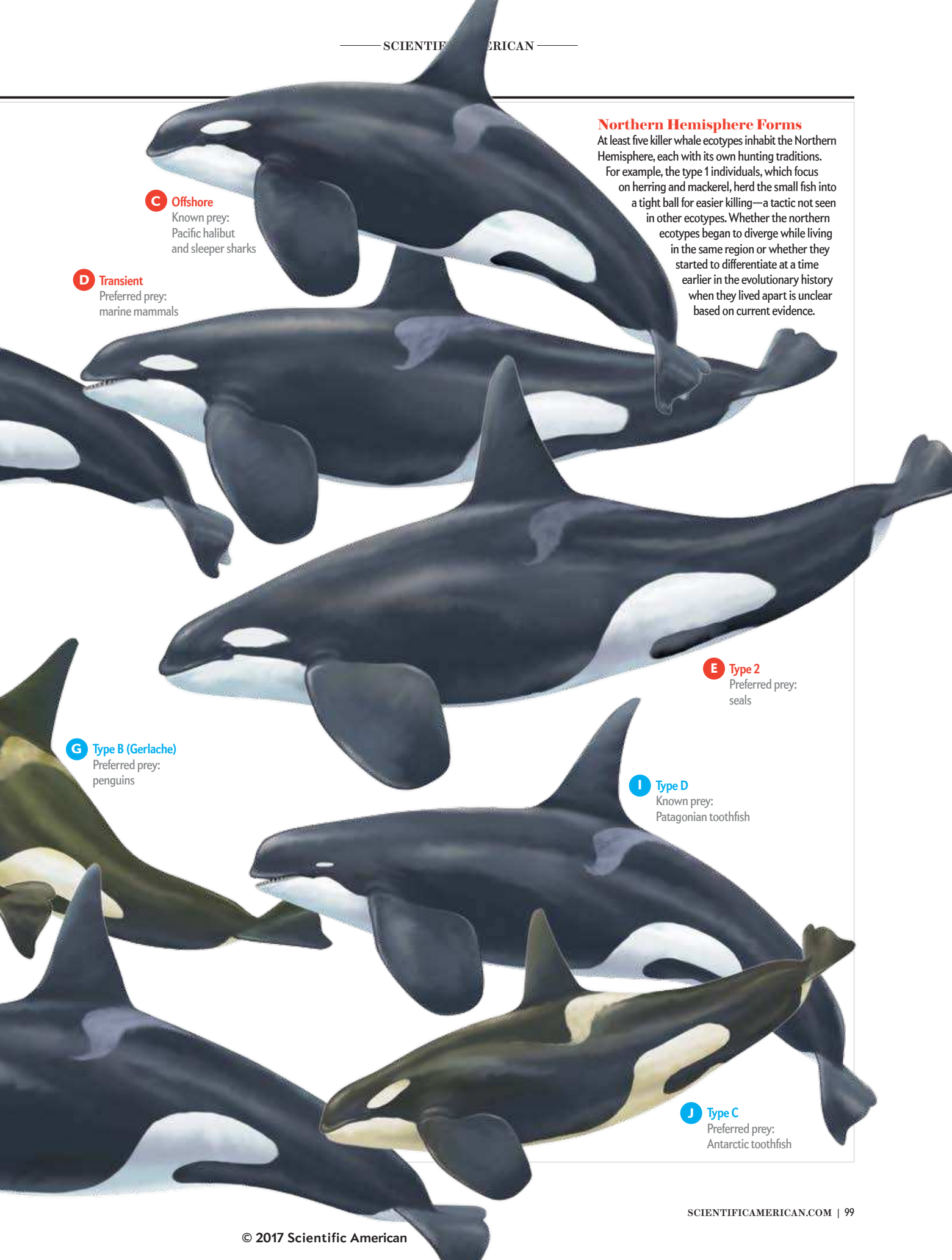
Northern Hemisphere Forms

At least five killer whale ecotypes inhabit the Northern Hemisphere, each with its own hunting traditions. For example, the type 1 individuals, which focus on herring and mackerel, herd the small fish into a tight ball for easier killing—a tactic not seen in other ecotypes. Whether the northern ecotypes began to diverge while living in the same region or whether they started to differentiate at a time earlier in the evolutionary history when they lived apart is unclear based on current evidence.



C Offshore
Known prey:
Pacific halibut
and sleeper sharks

D Transient
Preferred prey:
marine mammals

E Type 2
Preferred prey:
seals

G Type B (Gerlache)
Preferred prey:
penguins

I Type D
Known prey:
Patagonian toothfish

J Type C
Preferred prey:
Antarctic toothfish

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POD of killer whales surfaces off the coast of British Columbia.

reported that their genomic analysis of five killer whale ecotypes from the North Pacific and the Antarctic showed that these forms evolved from a common ancestor within the past 250,000 years. What is keeping them separate now? Breeding records maintained and occasionally published by SeaWorld, which houses killer whales originally captured in both the North Atlantic and the North Pacific, demonstrate that matings between different killer whale ecotypes produce viable and fertile offspring, in contrast to the usually infertile mules and hinnies that result from hybridization between horses and donkeys. It is therefore extremely unlikely that genetic incompatibilities between killer whale ecotypes are preventing interbreeding in natural populations. Rather mounting evidence suggests that cultural differences are to blame.

CULTURE CLASH

LIKE MANY ORGANISMS that have undergone speciation, killer whales are diversifying by exploiting different food sources and evolving various traits that presumably help them get those foods. Some of these distinguishing features are physical, such as the generally larger, stronger build of the mammal-hunting killer whales. But the most dramatic specializations have occurred in cultural behaviors related to food acquisition. Because these and other behaviors are found only in certain populations where they appear to be passed on between members of the same generation and from generation to generation through social interactions (so-called social learning), rather than being innate, biologists consider them to be cultural.

For example, populations of killer whales that hunt marine mammals have learned to intentionally strand themselves to capture inexperienced sea lion and elephant seal pups right off the beach. Scientists have observed this behavior in two groups of killer whales that are distinct from the previously mentioned ecotypes. One inhabits the waters around the Crozet Archipelago in the Indian Ocean between Africa and Antarctica; the other dwells near the Peninsula Valdés on Argentina's Atlantic Coast. Apparently both populations invented this hunting strategy independently in response to their prey choices and the physical characteristics of their hunting grounds, where deepwater channels and river outlets allow the killer whales to stay largely submerged until they are just meters away from their quarry.

In Antarctica, the large, pack ice form of the type B killer whales has invented another ingenious hunting strategy to gain access to seals: wave washing. The seals often haul out on small ice floats, where they feel safe from predators. But the pack ice killer whales have learned to create waves that wash the seals over the ice float and into the water, where they are easier to nab.

Type 1, fish-eating killer whales around Iceland and Norway, for their part, have developed an entirely different strategy—dubbed carousel feeding—to hunt the herring that form the mainstay of their diet. A pod of the killer whales will herd a school of herring into a tight ball close to the water surface, where the fish cannot escape into the depths. Then individual pod members will swim right into the ball and slam their tail fins into the fish to debilitate and kill them.

Killer whales even communicate differently depending on

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what they eat. Indeed, it is in their acoustic communication signals that the most astonishing cultural diversity is found. Like other dolphins, they use three different acoustic signals: echolocation clicks, which are used to navigate and to locate prey, and pulsed calls and whistles, both of which are used for communication with their compatriots. Not only do the pulsed calls and whistles differ among killer whales from different geographical regions, but they also differ among populations that inhabit the same region.

The reason for this intraregional variation in signal production and use becomes clear when one considers the different challenges the ecotypes face. Killer whales that hunt marine mammals, for example, must contend with the excellent underwater hearing ability of their quarry: eavesdropping prey can use any sound the killer whales produce to detect them and subsequently evade capture. Transient killer whales in the Northeast Pacific and mammal-hunting killer whales in the North Atlantic thus use acoustic signals only very sparingly; most of the time they swim and hunt in stealth mode. Fish-eating killer whales do not have the same problem, so they are typically very chatty with one another, and they do not skimp on echolocation when navigating and tracking prey.

Furthermore, many pulsed calls and, as some of my own research has shown, some whistles are highly stereotyped. That is, the signals can be further differentiated into discrete sounds, like letters in an alphabet. (There is no evidence to suggest that killer whales use these signals in any way that really resembles our human use of words and sentences, however. Rather the context within which a signal is used seems to provide the meaning.) These discrete sounds exhibit geographical variation and ecotype variation. But they also often vary among social groups within an ecotype. For instance, among northern resident killer whales—a population of fish-eating killer whales that inhabits the waters from approximately around the middle of Vancouver Island up into southeastern Alaska—each family unit has its own repertoire of seven to 17 discrete calls. Killer whale families that share a portion of their dialects are grouped together into acoustical clans: A-clan, G-clan and R-clan for the northern resident killer whales.

The different discrete call types and family dialects are so distinctive that those of us who work on these killer whale populations can assign individuals into the correct ecotype, clan (for northern resident killer whales) or even family unit, based on recordings of their discrete call repertoire alone. These differences figure importantly in mate choice. Genetic analyses of the northern residents by Lance Barrett-Lennard of the Vancouver Aquarium Marine Science Center have shown that call similarity largely mirrors genetic similarity. Most matings take place between members of different clans, which have correspondingly different calls. The finding implies that northern residents find other northern residents that sound different from themselves more attractive than those that sound similar. Thus, the dialects offer a nifty way to prevent inbreeding.

That killer whales have all these ecotype-specific customs and appear to dislike socializing and mating with foreigners from other ecotypes despite being biologically capable of doing so suggests that culture is keeping these ecotypes apart. Eventually, if this separation persists for enough generations, then these different ecotypes might evolve additional differences in their DNA that could render them genetically incompatible. Culture in killer whales thus has the potential to take the place of geographical isolation in facilitating speciation by preventing mixing between populations.

The killer whale findings raise interesting questions about diversification within the human family. Traditionally anthropologists thought that most selective pressures that shaped our evolution were the result of changes happening purely in our external environment. But recent genetic analyses indicate that a large part of our evolution might have resulted from certain, sometimes very locally restricted, cultural innovations. The practice of cattle farming has driven the evolution of lactose tolerance in certain European and African populations; the high-fat diet of Inuit people in Greenland has driven the evolution of a more efficient fat metabolism in that population. Although all modern human populations clearly belong to the same species and mix routinely with one another, for most of human prehistory, multiple human species shared the planet. Might culture have also played a role in driving speciation among those early members of the human family?

SEPARATE WAYS

DESPITE THE AMAZING ADVANCES in decoding how killer whales have diversified, scientists still have much to learn. Do other areas in less researched regions of the world also host sympatric killer whale ecotypes? Some preliminary studies hint that the oceans around Africa might; those around South America and southern Asia come to mind, too. Also, what are the communications systems of Antarctic and sub-Antarctic killer whales like, and what are their social structures? With the advent of modern tools for studying genomes, the future of speciation research in general—and killer whale research in particular—looks very bright. Perhaps in the not so distant future these and other new technologies will enable us to unequivocally determine what the geographical arrangements of killer whale populations were during all phases of their diversification.

Already we know that culture can divide killer whale populations that live side by side. Maybe a few years from now biologists will recognize these ecotypes as different species, each restricted to a certain geographical area of our oceans, each with its own very specific diet and customs, each with the potential to diverge and form yet more new twigs on the tree of life. SA

Rüdiger Riesch is a lecturer in evolutionary biology at Royal Holloway, University of London. His research focuses on the mechanisms that create, maintain and constrain biodiversity, with a special emphasis on speciation that occurs as a result of a population exploiting a new ecological niche.

MORE TO EXPLORE

Cultural Traditions and the Evolution of Reproductive Isolation: Ecological Speciation in Killer Whales? R. Riesch et al. in *Biological Journal of the Linnean Society,* Vol. 106, No. 1, pages 1–17; May 2012.

Phylogenomics of the Killer Whale Indicates Ecotype Divergence in Sympatry. A. E. Moura et al. in *Heredity,* Vol. 114, No. 1, pages 48–55; January 2015.

Geographic and Temporal Dynamics of a Global Radiation and Diversification in the Killer Whale. P. A. Morin et al. in *Molecular Ecology,* Vol. 24, No. 15, pages 3964–3979; August 2015.

Genome-Culture Coevolution Promotes Rapid Divergence of Killer Whale Ecotypes. A. D. Foote et al. in *Nature Communications,* Vol. 7. Published online May 31, 2016.

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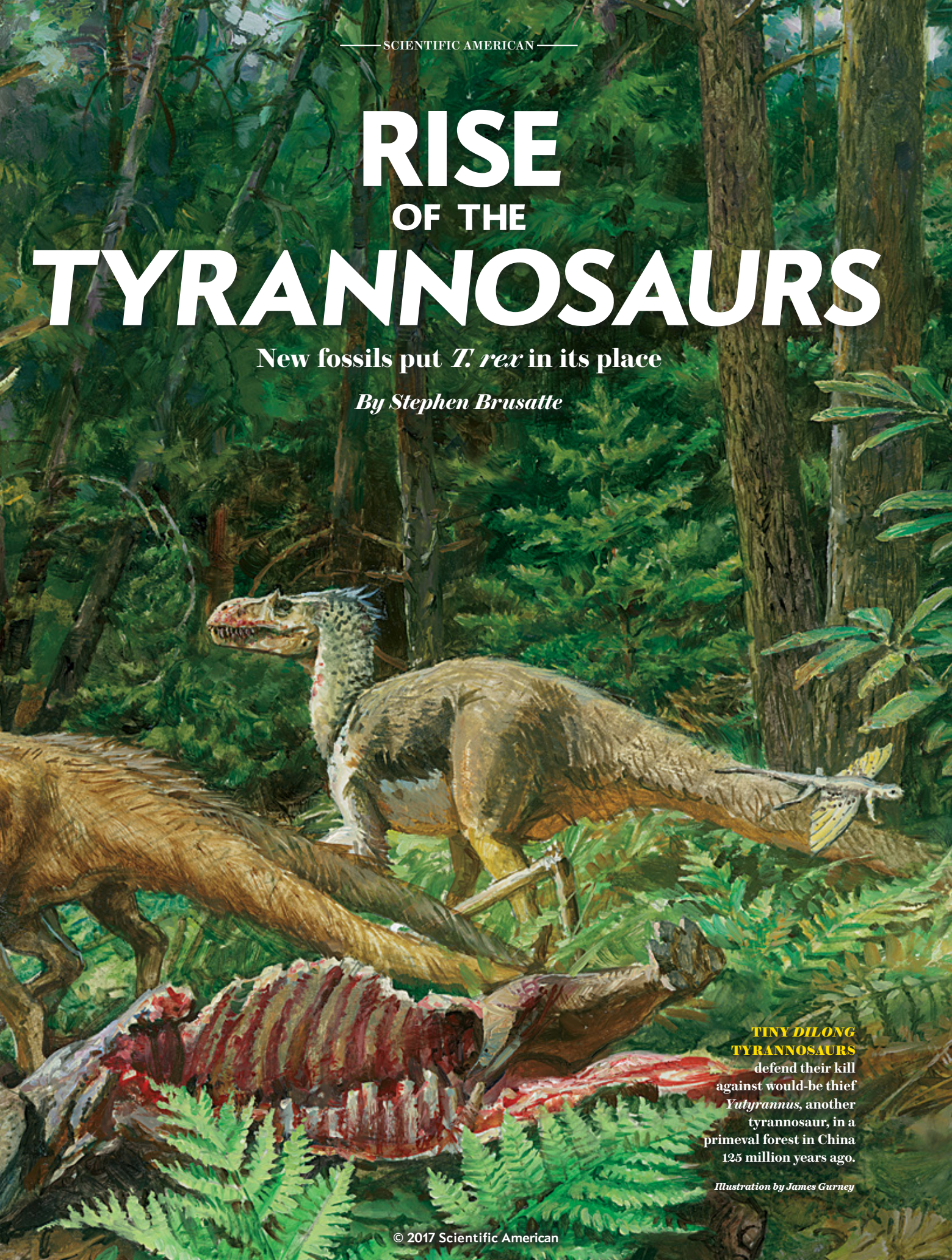
RISE OF THE TYRANNOSAURS

New fossils put *T. rex* in its place

By Stephen Brusatte



TINY *DILONG* TYRANNOSAURS defend their kill against would-be thief *Yutyrannus*, another tyrannosaur, in a primeval forest in China 125 million years ago.

Illustration by James Gurney

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ON A SWELTERING SUMMER DAY IN 2010, A CONSTRUCTION WORKER IN THE southeastern Chinese city of Ganzhou was digging the foundation for a building when his backhoe smashed into something hard. Climbing down to see what it was, he probably expected the worst—impenetrable bedrock, an old water main or some other nuisance that would inevitably delay completion of the sprawling industrial park his crew was racing to finish. But when the dirt and smoke cleared, a very different culprit came into focus: bones—lots of them, some enormous.

Construction did indeed stop that day because the bones turned out to be a major discovery. The worker had stumbled on a nearly complete skeleton of a bizarre new dinosaur species related to *Tyrannosaurus rex*. A few years later my Chinese colleagues invited me to help study the specimen, and in May 2014 we unveiled it as the latest addition to the tyrannosaur family tree: *Qianzhousaurus sinensis*. The formal name is something of a tongue twister, so we gave it a cheeky nickname, "Pinocchio rex," in reference to its peculiar long snout.

Qianzhousaurus is part of a surge of new tyrannosaur discoveries over the past decade that is transforming understanding of this group. Ever since *T. rex*'s discovery more than a century ago, the 13-meter-long, five-ton behemoth has dominated the limelight. Yet its evolutionary history has eluded investigators. During the 20th century scientists discovered a few close relatives of *T. rex* that were likewise impressively large and realized that *T. rex* was not a mere oddity: these big predators formed their own branch of dinosaur genealogy. But they struggled to understand when the tyrannosaurs originated, what they evolved from, and how they were able to grow so large and reach the top of the food chain. These questions have remained unanswered until now.

Since the beginning of this century researchers have recovered nearly 20 new tyrannosaur species at locations the world over, including the deserts of Mongolia and the frigid wastelands of the Arctic Circle. These finds have made it possible to piece together the tyrannosaur family tree, and the results are surprising: it turns out that tyrannosaurs were mainly marginal, human-sized carnivores for most of their history, achieving huge size and ecological dominance only during the final 20 million years of the Age of Dinosaurs, which began around 250 million years ago and spanned the Triassic, Jurassic and Cretaceous periods. The king of the dinosaurs, far from belonging to a dynasty of giant predators, actually had rather humble roots and was merely the last survivor of a startling variety of tyrannosaurs that lived across the globe right up until the asteroid impact 66 million years ago that brought the dinosaur era to a close and ushered in the Age of Mammals.

A STAR IS BORN

THE TALE OF HOW the tyrannosaur family history was uncovered begins with the discovery of *T. rex,* enabled by a man named Henry Fairfield Osborn. During the early 20th century Osborn was one of the most visible scientists in the U.S. He was president of the American Museum of Natural History in New York City and the American Academy of Arts and Sciences, as well as a *Time* magazine cover star. He used his considerable platform to push pet ideas on eugenics and racial superiority, so today he is often dismissed as just another bigot from years gone by. But Osborn was a clever paleontologist and an even better scientific administrator, and one of the best calls he ever made was to send a fossil collector named Barnum Brown out to the American West in search of dinosaurs.

Brown himself was an eccentric character, a man who hunted fossils in the dead of summer in a full-length fur coat and made extra cash spying for governments and oil companies.

IN BRIEF

Paleontologists have known about *T. rex* and other giant tyrannosaurs for decades. But they were unable to piece together when the tyrannosaurs originated and what they evolved from because they lacked the fossils to do so.

Recent fossil finds have gone a long way toward filling those gaps in scientists' understanding of this iconic group.

Together these discoveries reveal that tyrannosaurs have surprisingly deep—and humble—evolutionary roots.

Furthermore, the group encompasses a far greater diversity of forms than experts had anticipated—including some with truly bizarre anatomical features.

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The guy had good instincts, however, and in 1902 he made one of the most famous discoveries in the history of paleontology: a giant, meat-eating dinosaur from the badlands of Montana.

When this dinosaur was described a few years later, Osborn gave it a name whose brand value has stood the test of time: *Tyrannosaurus rex,* the "tyrant lizard king." It was an instant sensation, making headlines across the country. Osborn and Brown had unveiled the biggest, baddest, land-living predator ever.

T. rex became the quintessential celebrity dinosaur, the star of movies and museum exhibits around the globe. But this fame masked a puzzle: for nearly the entire 20th century scientists had little idea of how *T. rex* fit into the broader picture of dinosaur evolution. It was an oddball, a creature so much larger and so dramatically different from other known predatory dinosaurs that it was difficult to place in the dinosaur family album.

IF THE TYRANT KING WAS NOT FEARSOME ENOUGH ALREADY, JUST IMAGINE IT AS AN ENERGETIC, INTELLIGENT, BIG BIRD FROM HELL.

Over the next few decades, though, other paleontologists discovered a handful of close *T. rex* relatives that lived at about the same time—in the late Cretaceous—at sites in North America and Asia dated to between 84 million and 66 million years ago. These tyrannosaurs—*Albertosaurus, Gorgosaurus, Tarbosaurus*—are quite similar to *T. rex:* humongous apex predators that thrived during the last gasp of dinosaur history. Although the fossils were impressive, they did little to illuminate the origins of the group.

MODEST BEGINNINGS

A NUMBER OF THE RECENT discoveries that are helping to fill the considerable gaps in our knowledge of tyrannosaurs have come from unexpected locales. The stereotypical dinosaur find involves intrepid paleontologists trekking to some far-flung corner of the desert in western North America, Argentina, the Gobi or the Sahara and braving the heat, dust and snakes to hack fossils out of their rocky tombs. But dinosaurs, including tyrannosaurs, are turning up across the world now, even in the far northern reaches of Russia, where paleontologists instead need to cope with bone-chilling cold in winter and humid, mosquito-infested summers.

Alexander Averianov, my colleague from the Zoological Institute of the Russian Academy of Sciences in St. Petersburg, is one of these paleontologists. In 2010 his team announced a provocative discovery from the vast Krasnoyarsk region of central Siberia: a jumble of bones from a small, meat-eating dinosaur that lived well before *T. rex*—about 170 million years ago in the Middle Jurassic period—and would have been about the size of a human. They named it *Kileskus,* based on the word "lizard" in a local language. It turned out to be a vital clue to the rise of tyrannosaurs.

At first glance, *Kileskus* does not appear very impressive. It certainly does not look anything like *T. rex.* If *T. rex* had been living in Russia during the Middle Jurassic, it could have swatted *Kileskus* away like a fly, even with its pathetic little arms. But *Kileskus* exhibits unmistakable similarities to another small carnivore, *Guanlong,* that lived about 10 million years later in China and was described in 2006. For instance, both animals have a gaudy mohawklike crest of bone running along the top of the skull. And *Guanlong,* which is known from much more complete specimens than *Kileskus,* possesses features that are seen only in tyrannosaurs, such as fused nasal bones in the snout. These shared traits are signs of common ancestry: the modest, almost forgettable *Kileskus* and *Guanlong* are the ancestral stock from which the great *T. rex* arose.

These two finds painted a startling picture of the dawning of tyrannosaurs. They revealed that the group did not begin as massive superpredators, as many researchers had thought when the first tyrannosaurs were found, but rather as second- or third-tier carnivores living in the shadow of giant predators from distantly related groups such as allosaurs and ceratosaurs. In addition, tyrannosaur roots run far deeper than anyone expected. They lived at a time when the supercontinent Pangea had not yet fully broken apart, so that animals could disperse relatively easily across landmasses. This geography explains why early tyrannosaurs have since turned up in Russia and China, and slightly later species have emerged from the U.S., U.K. and perhaps even Australia (the taxonomic affiliation of some Australian predatory dinosaurs is a matter of debate). Together the specimens also show that it took an amazingly long time for tyrannosaurs to rise to power: there was a greater separation in time between the ancestral tyrannosaurs and *T. rex* (at least 100 million years) than between *T. rex* and humans (66 million years).

WARM AND FUZZY

ALTHOUGH THE TYRANNOSAURS were slow to reach truly gigantic proportions, that delay does not mean their evolution stagnated in the interim. Mounting evidence indicates that the group underwent considerable diversification long before the likes of *Tarbosaurus* and *T. rex* appeared. Striking examples of this proliferation have come from Liaoning Province in northeastern China.

Liaoning is not the most beautiful place in the world. Even though I grew up in the boring plains of the American Midwest, I find it difficult to keep my eyes open during the three-and-a-half-hour train ride from Beijing through kilometer after kilometer of hilly countryside draped with haze and dotted with farms and billowing smokestacks. But this is a holy land for fossil hunters.

Over the past two decades farmers all around this region have collected thousands of dinosaur skeletons. Repeated volcanic eruptions around 120 million to 130 million years ago quickly buried the ill-fated creatures in ash and mud, preserving their remains in exquisite detail. Among the many beasts found in this Cretaceous Pompeii are two intriguing species of tyrannosaurs. My colleague Xu Xing of the Institute of Vertebrate Paleontology and Paleoanthropology in Beijing announced the first of these species, *Dilong,* in 2004. Roughly the size of a golden retriever, it had long arms for catching prey and a lithe, leggy skeleton built for speed. The second species, which Xu described in 2012, is a very different type of animal. At eight to nine meters long and about a ton in mass, this animal—named *Yutyrannus*—probably sat at or near the top of the food chain. Both tyrannosaurs are found in the same rock formation and may have lived side by side approximately 125 million years ago. Together these species, which exhibit the fused nasal bones and other hallmarks of tyrannosaurs, demonstrate that by the Early Cretaceous tyrannosaurs had branched off into a range of new species filling different ecologi-

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FINDINGS

All in the Family

A rash of fossil discoveries in recent years has filled in the tyrannosaur family tree. The finds show that tyrannosaurs were a surprisingly diverse bunch yet slow to evolve the gigantic proportions associated with the mighty *T. rex*.

The Cast

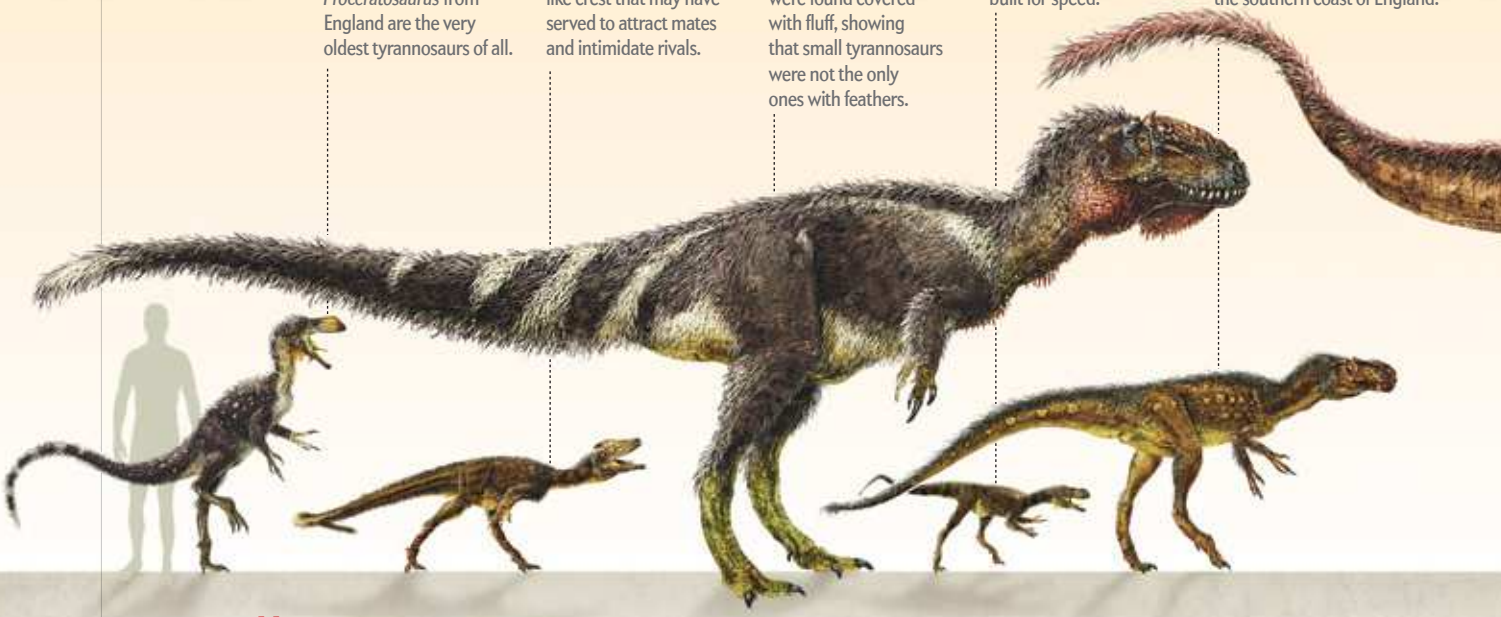
1 ***Kileskus*** Discovered in central Siberia, this bantam species and *Proceratosaurus* from England are the very oldest tyrannosaurs of all.

2 ***Guanlong*** This Chinese tyrannosaur possessed a distinctive mohawk-like crest that may have served to attract mates and intimidate rivals.

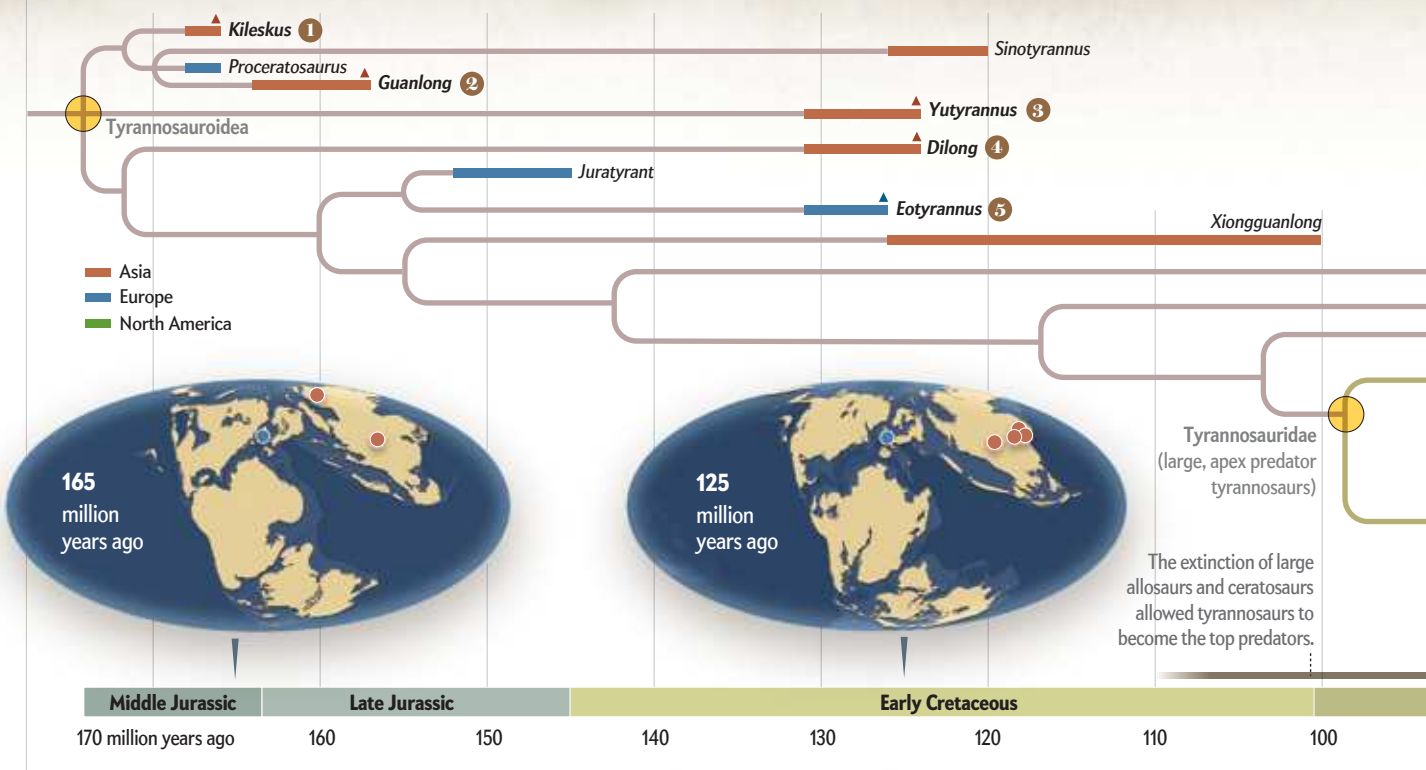
3 ***Yutyrannus*** Fossils of this large-bodied species from China were found covered with fluff, showing that small tyrannosaurs were not the only ones with feathers.

4 ***Dilong*** The tiniest tyrannosaur, this leggy Chinese form was built for speed.

5 ***Eotyrannus*** Fossils of this long-fingered species come from the Isle of Wight off the southern coast of England.



From Humble Beginnings ...



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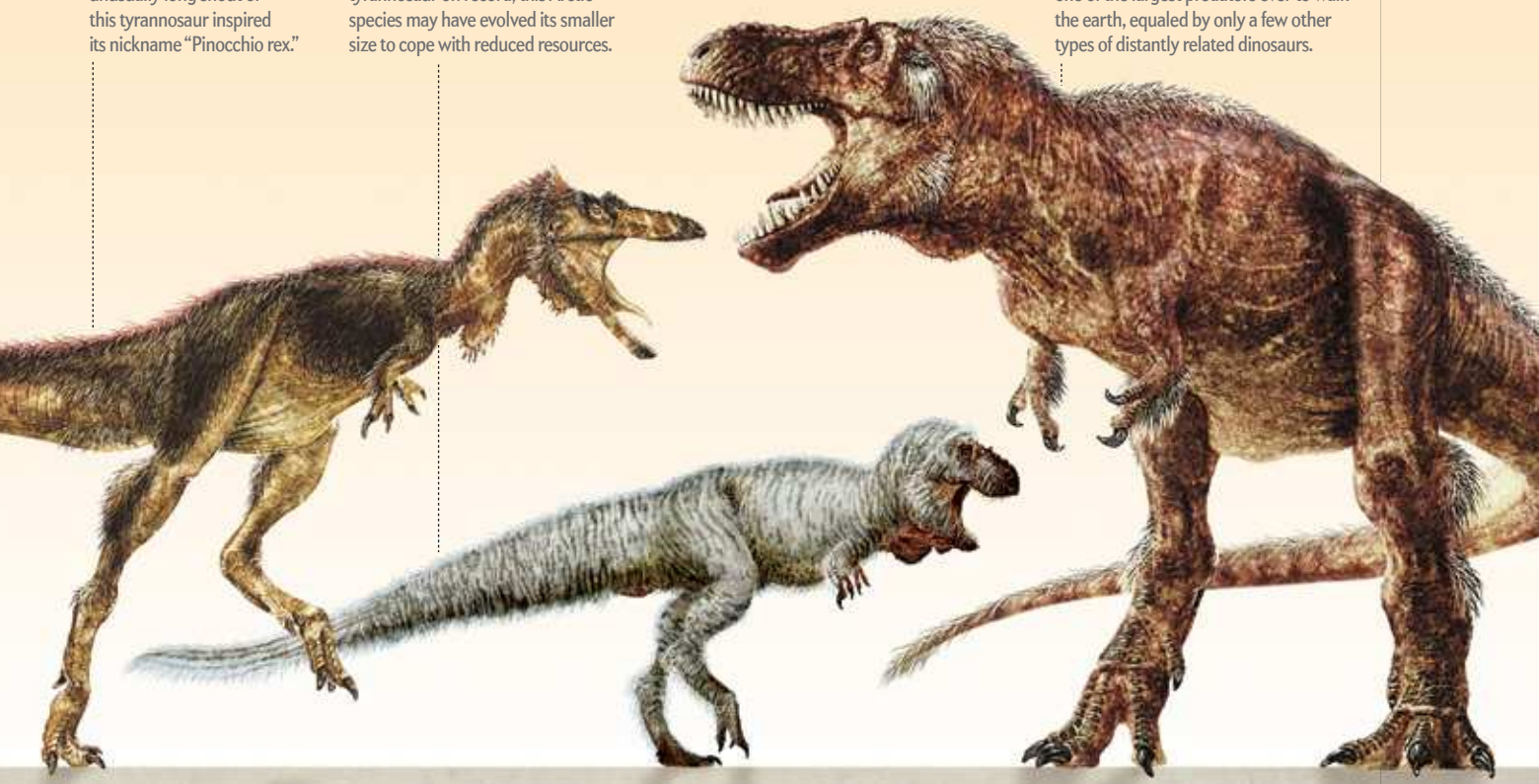
6 ***Qianzhousaurus*** The unusually long snout of this tyrannosaur inspired its nickname "Pinocchio rex."

7 ***Nanuqsaurus*** The most northerly tyrannosaur on record, this Arctic species may have evolved its smaller size to cope with reduced resources.

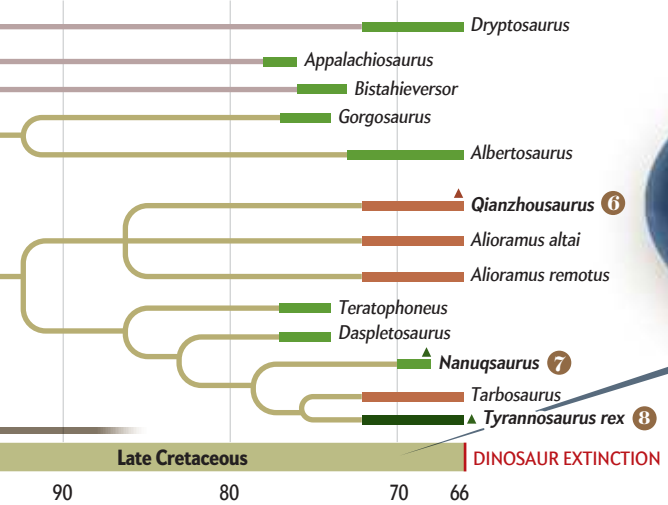
8 ***Tyrannosaurus rex*** The tyrant king was one of the largest predators ever to walk the earth, equaled by only a few other types of distantly related dinosaurs.

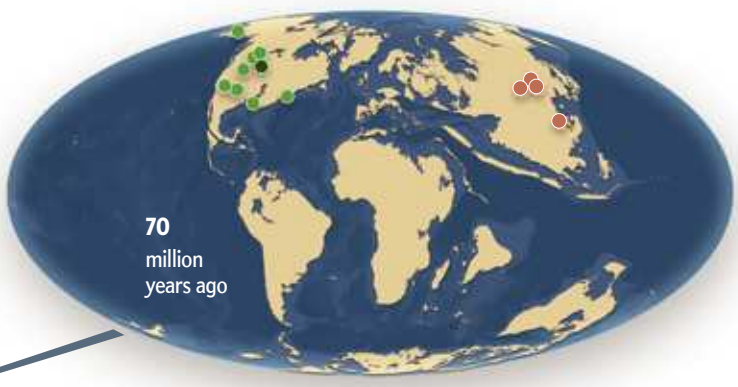


… To Apex Predators

Tyrannosaur Biogeography

The growing tyrannosaur fossil record shows that this group was far more widespread than previously thought, with finds emerging from the U.S., U.K., China, Russia and possibly Australia. Tyrannosaurs were able to disperse far and wide because they evolved at a time when the continents had yet to fully break apart, making it easy to cross from one landmass to another.





SOURCE: PLATE TECTONIC AND PALEOGEOGRAPHIC MAPS BY C. R. SCOTESE, PALEOMAP PROJECT, 2009 (maps)

Illustration by Todd Marshall (dinosaurs), Graphics by 5W Infographics

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LONG-NOSED *QIANZHOUSAURUS*, found at a construction site in China in 2010, shared ecosystems with much larger-bodied tyrannosaurs, probably by using its stealth and speed to pursue smaller prey.

cal roles and that some were experimenting with larger body size.

Dilong and *Yutyrannus* are also important for another reason. Paleontologists once viewed dinosaurs as scaly, plodding, overgrown reptiles. In recent years, however, researchers have found evidence that a number of dinosaur species sported downy coats rather than scales and were generally more dynamic and smarter than they had previously been thought. Which is to say, they were more like birds than reptiles. *Dilong* and *Yutyrannus* establish beyond a doubt that tyrannosaurs fit this description. The bones of these species are covered with a thick, feathery fluff—not the quill-pen feathers that make up the wings of living birds but simpler, filamentlike feathers that look like hair. Unlike birds, tyrannosaurs certainly were not flying. Instead they probably used their feathers for display or to keep warm. The presence of feathers in tyrannosaurs and many other kinds of dinosaurs makes it very likely that the great *T. rex* was feathered, too. If the tyrant king was not fearsome enough already, just imagine it as an energetic, intelligent, Big Bird from Hell.

RISE OF THE KINGS

THE NEW DISCOVERIES from Russia, China and elsewhere show that tyrannosaurs were doing quite well from the Middle Jurassic into the Early Cretaceous. They may not have been top dogs, but they had found their niche as a steady, if unspectacular, group of stealthy, fleet-footed predators. But then something changed. Sometime between 85 million and 110 million years ago, during the middle part of the Cretaceous, dinosaur ecosystems underwent a radical restructuring. The allosaurs and ceratosaurs that had long occupied the apex of the food pyramid largely disappeared, and tyrannosaurs assumed the top predator role on the northern continents. Exactly why this happened is unclear because dinosaur fossils from the Middle Cretaceous are extremely rare. A mass extinction about 94 million years ago—when temperatures increased and sea levels fluctuated—may be to blame.

One recent fossil find—the newest tyrannosaur species known to science—may offer some clues. Discovered in Uzbekistan, it was named *Timurlengia* in early 2016, after the great Central Asian warlord Tamerlane. *Timurlengia* is about 90 million to 92 million years old and only about the size of a horse, so it was not a top-of-the-food-chain monster. In fact, it was still living underfoot of the allosaurs. But what *Timurlengia* had was a large brain and an ear attuned to hearing a wide range of sounds, which we confirmed with CT scans of its skull. *Timurlengia* suggests that tyrannosaurs got smart before they got big—and maybe it was the evolution of brains that helped them persist in the shadows and later allowed them to evolve their brawn.

However they got there, tyrannosaurs flourished once they reached the apex of the food chain. During the final 20 million years of the Cretaceous, tyrannosaurs reigned supreme in North America and Asia as multiton, tiny-armed, huge-skulled superpredators. They bit so hard that they crunched through the bones of their prey. They grew so fast that they put on a few kilograms of mass every day during their teenage years. And they lived so hard that paleontologists have yet to find an individual that was more than 30 years old when it died.

Yet as successful as the colossal tyrannosaurs were in North America and Asia, they do not seem to have ever gained a foothold in Europe or the southern continents, where other groups of large predators prospered instead. Reconstruction of the earth's climate and continental configuration during the Late Cretaceous hints at why. The world at that time was very different from the setting in which smaller tyrannosaurs first evolved. The continents had drifted much farther apart, reaching positions similar to the ones they occupy today. Furthermore, dramatically higher sea levels bisected North America and reduced Europe to a smattering of small islands. *T. rex*'s earth was a highly fragmented

COURTESY OF JUNCHANG LÜ *Chinese Academy of Geological Sciences' Institute of Geology*

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planet. As a result, champions in one region might not be able to conquer another for one simple reason: they could not get there.

PERSISTENT VARIETY

IN THE REGIONS where mega tyrannosaurs such as *T. rex* did rise to power, one might expect these brawny forms to have edged out other, daintier tyrannosaurs. The latest fossil discoveries suggest otherwise. Amazing new finds have revealed an unappreciated diversity of tyrannosaurs up and down the food chain, even during those last few million years of the Cretaceous, when *T. rex* and kin ruled unchallenged.

The Pinocchio-nosed *Qianzhousaurus,* from the Chinese construction site, is a prime example. When my colleague Junchang Lü of the Chinese Academy of Geological Sciences' Institute of Geology first showed me photographs of the specimen at a conference in 2013, I was gobsmacked. Here was a tyrannosaur from the latest part of the Cretaceous that was strikingly different from the tyrant lizard king. It was noticeably smaller—just about eight to nine meters long and probably around a ton in mass. Still not any animal you would want to run into in a dark Cretaceous alley but a waif compared with *T. rex*. Even weirder, its skull was long, narrow and delicately constructed, unlike the deep, muscular, bone-crunching skull of its famous cousins.

Lü invited me to help him describe the new Chinese fossil because I had studied two other peculiar long-snouted tyrannosaurs, discovered decades earlier, that had long confused scientists. The first of these creatures was known from part of a skeleton found in Mongolia by a Russian team in the 1970s. They called it *Alioramus remotus* and suggested that it was an aberrant long-skulled tyrannosaur. But very few paleontologists were able to study the specimen during the cold war, so it remained debatable whether it was a weird new species or just a young representative of the existing tyrannosaur species *Tarbosaurus*. A few decades later, in the early 2000s, a joint Mongolian-American team led by my Ph.D. adviser, Mark Norell of the American Museum of Natural History, discovered a much more complete and better preserved specimen of *Alioramus*. On the first day of my Ph.D. studies Norell took me into the museum's prep laboratory, showed me the skeleton and told me to get to work studying it. In 2009 we announced it as a new species, *Alioramus altai*. This skeleton appeared to be distinct from *Tarbosaurus*, but because it came from a juvenile individual (as revealed by its internal bone structure), we could not rule out the possibility that its seemingly unique traits were instead the product of incomplete growth.

Sometimes debates like this one rage for decades, as paleontologists await new fossils to break a stalemate. In our case, it took only a few years, along with the dumb luck of the backhoe operator. The *Qianzhousaurus* skeleton discovered in Ganzhou had the same long snout, delicate build and small body size of *Alioramus,* but it clearly belonged to a much older and more mature individual. It was the clincher: long-snouted tyrannosaurs were distinct species that lived across Asia during the very end of the Cretaceous, probably filling a second-tier predator role on the food chain below *Tarbosaurus*.

Qianzhousaurus was not the only petite tyrannosaur to share the planet with the heavyweights. Just about two months before we published our description of *Qianzhousaurus,* my American colleagues Anthony Fiorillo and Ronald Tykoski, both at the Perot Museum of Nature and Science in Dallas, Tex., revealed an even stranger latest Cretaceous tyrannosaur from the frosty Arctic Circle of Alaska, called *Nanuqsaurus*. It is known from just a few bones that look a lot like the corresponding bones in *T. rex* but with one incredible difference: they are about half the size. The obvious explanation is that the bones belong to a baby tyrannosaur, but shockingly they have thickened sutures—the "seams" between adjacent bones that are only seen in adults. Fiorillo and Tykoski came up with an idea that may sound farfetched but one I think is very plausible: Arctic tyrannosaurs evolved small bodies because their resource-poor habitat could not support larger species. Many modern island-dwelling animals have undergone dwarfing for that same reason. So while *T. rex* ruled to the south, a Mini Me tyrannosaur patrolled the northern wilderness.

BEYOND THEIR CONTROL

THESE LATEST ADDITIONS to the tyrannosaur family tree have illuminated the evolutionary history of this charismatic group, but key questions remain. Where did tyrannosaurs originate, and did they get their start even earlier than the Middle Jurassic, perhaps during the Early Jurassic, a time when we have few fossils from around the world? Did tyrannosaurs also live across the southern continents during the Middle Jurassic/Middle Cretaceous? Most of their fossils are from the northern continents, except for one enigmatic bone from Australia. But we know that many dinosaur groups were globally widespread during the Middle Jurassic/Middle Cretaceous, so maybe tyrannosaurs were, too. Other unknowns concern their biology. What kind of feathers did the largest tyrannosaurs like *T. rex* have, and what purposes did they serve? And how did *Qianzhousaurus* and *Alioramus* use their distinctive long snouts?

Incomplete as the tyrannosaur story is, it still reveals a deeper truth about evolution—namely that it is not predictable. When tyrannosaurs originated more than 170 million years ago, no one would have guessed that these puny stalkers would come to rule entire continents. They were not preordained for success. Rather they had to navigate more than 80 million years of living in the shadows, biding their time until environmental changes gave them the opportunity to become apex predators. And then one day, when the tyrannosaurs were at the peak of their game, an asteroid fell from the sky and they disappeared. Their strength and size could not save them as wildfires raged, ecosystems collapsed and mammals began their march to the top.

Stephen Brusatte is a paleontologist at the University of Edinburgh in Scotland. His research focuses on the anatomy and evolution of dinosaurs. Brusatte is author of more than 70 technical articles and five books on dinosaurs, and he serves as the "resident paleontologist" for the BBC's *Walking with Dinosaurs* program.

MORE TO EXPLORE

Tyrannosaur Paleobiology: New Research on Ancient Exemplar Organisms. Stephen L. Brusatte et al. in *Science,* Vol. 329, pages 1481–1485; September 17, 2010.

The Phylogeny and Evolutionary History of Tyrannosauroid Dinosaurs. S. L. Brusatte and T. D. Carr in *Scientific Reports,* Vol. 6, Article No. 20252; February 2, 2016.

New Tyrannosaur from the Mid-Cretaceous of Uzbekistan Clarifies Evolution of Giant Body Sizes and Advanced Senses in Tyrant Dinosaurs. Stephen L. Brusatte et al. in *PNAS,* Vol. 113, No. 13, pages 3447–3452; March 29, 2016.

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SWIMMERS UNDER PRESSURE

Jellyfish manipulate physics to become the most efficient animals moving in the sea

By Josh Fischman

JELLYFISH NEVER STOP. Twenty-four hours a day, seven days a week, they move through the water in search of food such as shrimp and fish larvae, on journeys that can cover several kilometers a day. They are more efficient than any other swimmer, using less energy for their size than do graceful dolphins or cruising sharks. "Their cost of transport—the oxygen they use to move—is 48 percent lower than any other swimming animal," says Bradford J. Gemmell, a marine biologist at the University of South Florida. By studying moon jellies, the species *Aurelia aurita,* Gemmell and other researchers have recently found that jellyfish pull off this feat by creating zones of high and low pressure around their body that alternately suck and push them forward.

Scientists once believed that jellies traveled so easily because they were light, mostly water. But water has mass, and mass still has to be moved. So Gemmell, with engineer John Dabiri of Stanford University and their colleagues, took a close-up look. They put a jellyfish in a tank and dropped tiny glass beads into the water. By illuminating the beads with lasers, they could track their movements with a high-speed camera, essentially making the water velocity and pressure visible around the animal.

When the animal contracted its bell—the dome that forms much of the jellyfish body—it created lower pressure outside the bell and higher pressure within. Because objects move from high to low pressure, the moon jelly got pulled forward, the scientists noted in November 2015 in *Nature Communications*.

Then the researchers got a surprise. When the jelly relaxed the bell margin, letting it flare out, the high-pressure water below the animal rose up into the bell. "It gave the moon jelly a secondary bump forward, even while it relaxed," Gemmell says. To make these moves, the jelly needs to flex the bell margin up and down. Jellyfish have muscles, but most go around the bell like a stack of rubber bands. That arrangement is good mainly for squeezing. Recently, though, Richard Satterlie, a biologist at the University of North Carolina Wilmington, discovered other muscles at the margin that stick out at angles. Those fibers let the jelly bend its edge, moving water around it, and make for a very effective swimmer. SA

ALEXANDER SEMENOV

Josh Fischman is a senior editor at *Scientific American.*

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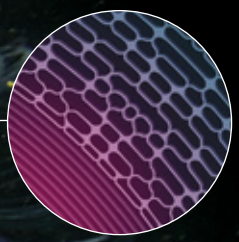
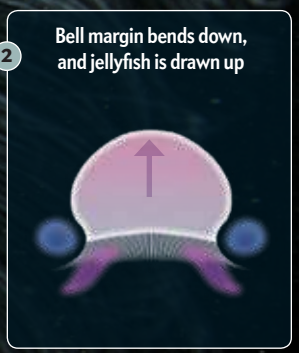
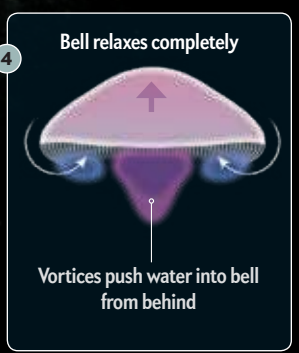
Muscle fibers generally circle the bell, but at the margin, they form a mesh, helping it bend.







The Jellyfish Swim Stroke

Jellyfish create zones of high and low pressure around themselves, then move from one to the other. By dropping tiny glass beads in a water tank with a jellyfish, a team of scientists was able to see that a vortex—a relatively low-pressure spinning doughnut of water—rolls down the jelly. Seen here as a cross-sectional slice, the vortex (*blue*) appears as two wheels of water 1. As the jelly contracts, it creates higher pressure within its bell, and the animal is pulled ahead to lower pressure 2. By flexing the edge of its bell, the jelly moves the vortex down and underneath 3. There the vortex pushes water up as it spins, giving the jelly an extra shove 4.

Illustrations by Eleanor Lutz

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END NOTE

Big Hummer

Our gorilla cousins sing as they supper *By Steve Mirsky*

WHERE, AN OLD JOKE ASKS, does a 400-pound gorilla sleep? Anywhere it wants to, the superannuated gag answers. In keeping with that line of reasoning, a 400-pound gorilla should similarly hum anytime it wants to. The scientifically verified answer, however, is that the gorilla in question actually hums when he's eating—if the gorilla in question is a socially prominent male, anyway, according to a study recently published in the journal *PLOS ONE*. The humming sounds more like rumbling Dolby Audio in a theater showing a *Fast & Furious* movie than what you and I might come up with when we're doing the dishes. But it's definitely a hum coming out of that huge, hairy head.

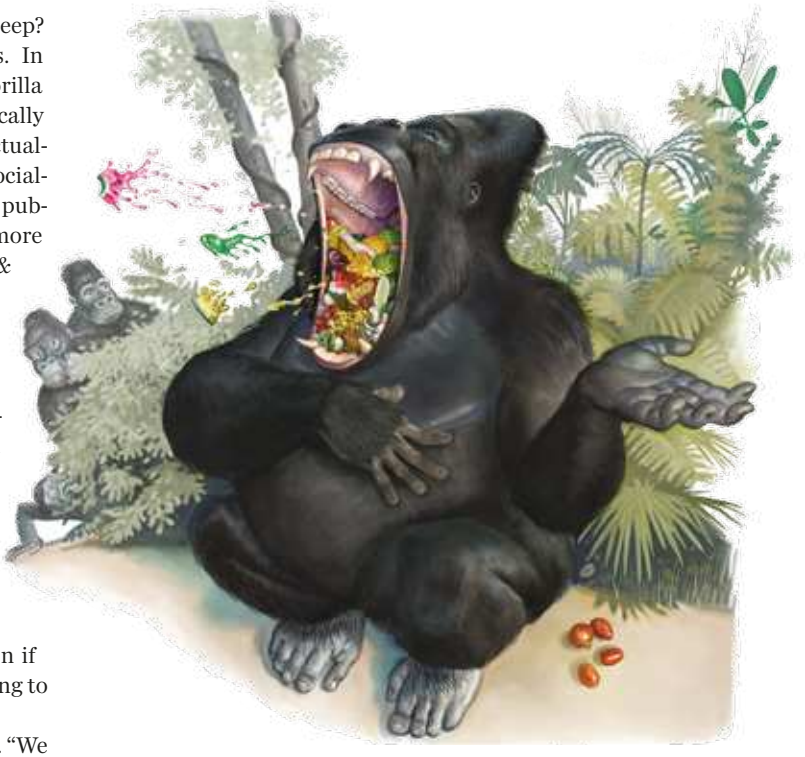
The same study found that some gorillas may even sing when they're chewing on a favorite piece of vegetation. (And you thought it was impolite to even *talk* with your mouth full.) Gorilla singing doesn't approach the mellifluous stylings of, say, the Monkees, but it's vaguely musical, and the logical thing to call this sound that clearly isn't humming would be singing. Just as humans who perform "Aba Daba Honeymoon," with the immortal line "Baba daba daba daba daba daba dab, said the monkey to the chimp," are certainly singing, even if the work is "the nadir of all American expression," according to Thomas Pynchon.

That gorillas produce such noises was not a total shock. "We know from studies on chimpanzees and bonobos that great apes produce certain vocalizations while they're feeding, so-called food-associated calls," said one of the authors of the study, Eva Luef of the Seoul National University, in an interview for *Scientific American*'s Science Talk podcast. "And our study wanted to investigate whether gorillas do the same."

So Luef and her colleagues trooped off to the Republic of the Congo to spend some time with two different populations of western lowlands gorillas, which have the easy-to-remember Linnaean subspecies designation of *Gorilla g. gorilla*. (See if you can guess what the "g" stands for.)

Primatologist Dian Fossey, who died in Rwanda in 1985, noted that gorillas hum and sing. She categorized such sounds as "belch vocalizations," which often seemed to signal contentment—can you believe some people still don't accept that gorillas and humans have a common ancestor?

The current research, however, is the first to really track the vocalizations and connect them to specific behaviors. "And we found that it was [males—blackback adolescents and silverback adults—that] were the most frequent callers," Luef revealed. "This is not surprising as adult males are usually the most frequent callers, concerning any gorilla vocalization. And then we found that the food calls were produced when they were feeding on certain foods. So aquatic vegetation or seeds elicited a lot of food calls. And … they never called when they were eating insects like termites or ants." Because feasting on *Formicidae* or ingesting *Isoptera* is nothing to sing about. Even among gorillas.



So what's with all the *Sturm und Sang?* "We believe that the food calls have a social function in gorillas," Luef said. "They may signal to [other gorilla] listeners that an individual is busy eating at the moment. Silverback males have a special role in gorilla society…. They are most often the ones making group decisions. So when the silverback sits and eats, the others eat as well. And [when] he gets up and starts to … travel in the forest…, the others follow him. So it makes sense for the silverback to signal to his group mates that he's still eating and then signal that he has finished eating when he stops calling." In other words, humming and singing may be the dominant male's Do Not Disturb sign. And his eventual silence could be gorilla for "Ladies and almostmen, may I have your attention?"

In fact, Luef and her colleagues plan to do more in-depth analysis of gorilla vocalizations to see if they can learn anything about how we came to yap. They want to study "how the gorillas compose their food songs," she said, "and whether they possess a certain repertoire of song notes, which they combine into their little food songs. That would be more similar to human language because [we have] a certain repertoire of sounds we can make, and we combine them into words and different languages. So if gorillas could do the same with their songs, that would just be amazing." Aba daba indeed. SA

Steve Mirsky has been writing Anti Gravity, *Scientific American's* humor column. since a typical tectonic plate was about 35 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

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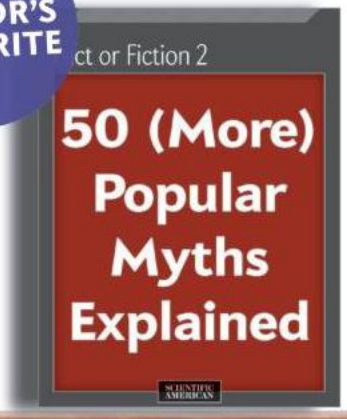

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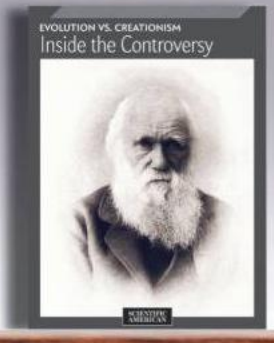

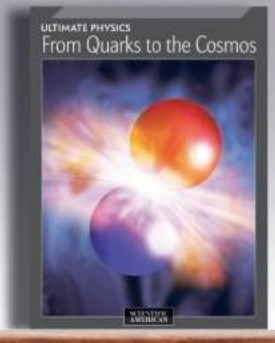

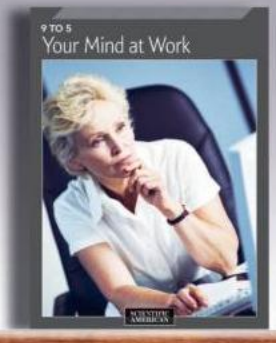

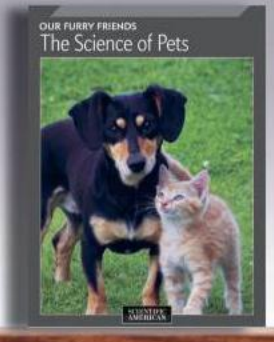

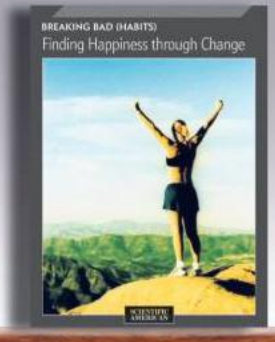

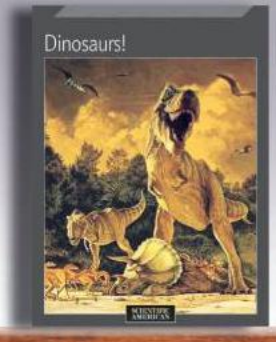

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